CORRELATION OF MONSON'S SPHERE AND SOME OTHER DENTOFACIAL VARIABLES TO TEMPOROMANDIBULAR JOINTS (TMJs) IN THE CHINESE POPULATION

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ABSTRACT

Purpose: The purpose of this study was to investigate the correlation of Monson's Sphere along with several dentofacial variables to the morphologic changes of condyles (condylar height in this case), as well as the possible mechanism that may govern this correlation. These variables are: the discrepancy of the mandibular and maxillary spheres, ANB (anterior-posterior relationship of the maxilla with the mandible), Bonwill's Angle, Overbite, Overjet, the angle of mediolateral axes of two condyles and the distance between the two condyles.

Materials and methods: CT (Computed Tomography) DICOM (Digital Imaging and Communications in Medicine) data of 54 Chinese patients were collected, including 43 females and 11 males aged from 11 to 49 years old. The coordinates of the dental, craniofacial and temporomandibular landmarks were measured through a DICOM viewer. A linear regression model was used to fit the sphere to the coordinates of the dental and temporomandibular landmarks. As well, condylar height and other variables were calculated from the coordinates of the landmarks. Pearson Correlation was performed to illustrate the bivariate correlation of the variables in couples. The difference among the groups categorized by the fixed factors including gender, age, ANB and so on, was tested by ANOVA, and the influence of multiple independent variables on dependent variables was examined.

Results: From the data analysis, the mean radius of Monson's Sphere in the maxilla is 92.42 mm and the mean radius in the mandible is 85.69 mm. Condylar height is correlated to the angle of the mediolateral axes of two condyles positively, and to Overjet, ANB and Bonwill's angle in a negative way. The discrepancy of the two Monson's spheres seems to have a linear correlation with both Overjet and Overbite, and the group with the lower values of condylar height are more likely to obtain a portfolio of the greater values of Overjet, Overbite and the excessive discrepancy of the two spheres.

Conclusion: The average radius of the mandible Monson's Sphere is less than 100mm and the radii of only 3 out of 54 subjects are around 100 mm; however, the average distance between two submits of condyles is 100.87 mm. The group of Angle Classification Class II Division I seem to be the high-risk population with the feature of lower condylar height. This finding may pave the way for further research on the relationship between occlusion and temporomandibular joints. Note that since all the results and conclusions herein come from a specific set of populations (Chinese in particular), generalization to other populations may need to be applied with careful and informed consideration.

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CHAPTER 1 INTRODUCTION

Biting and chewing are the fundamental functions of the masticatory system. The jaw, which is a detached bony component of the skull, contains teeth in the middle and terminates in condyles on the left and right ends. Fossae are located at the bottom of a skull and accommodate the condyles. The temporomandibular joints (TMJs) comprise condyles, fossae, cartilages and other soft tissues. Mastication is fulfilled by means of the masticatory muscles that originate from the skull and insert onto the jaw. During biting and chewing, the jaw functions as an articulated structure.

As a specific dentofacial feature, Monson's Sphere is rarely discussed with respect to TMJs. Further, relationship between the morphology or structure of TMJs and dentofacial characteristics remains unclear. Although numerous studies have been undertaken toward understanding the possible effects of occlusal factors in temporomandibular disorders (TMD), only a few of those have explored the correlation of the morphological features of TMJs and dentofacial characteristics, and little attention has been focused on not only the motion of the mandible but also the potential association of its motion to TMJs with the foregoing correlation. From a systemic point of view, the masticatory system may reach a compromise after failure of a vulnerable part or parts during the masticatory function, such as tooth fracture, alveolar bone resorption, TMD and so on.

Several general research questions were proposed based on the literature studies (see chapter 2 for details) and are described as follows:

1. Can Monson's Sphere be identified in both the maxilla and mandible with respect to TMJs?
2. Are the morphological features of TMJs perhaps correlated to some of the dentofacial characteristics?
3. If there is a correlation, how may the biomechanical mechanism account for this correlation?

This thesis study attempted to answer the above questions. The following specific objectives and their scopes were thus defined to facilitate the study:

- *Objective 1*: To measure the radii of Monson's Sphere in the maxillary and mandibular dentitions with respect to TMJ condyles in the Chinese population. The measurements were made on CT DICOM data.
- *Objective 2*: To investigate a potential correlation between specific dentofacial factors and TMJ features, especially the condylar height, through analysis of CT DICOM data.
- *Objective 3*: To study the biomechanical mechanism of this correlation. This study was restricted to speculation only; no further experimentation was conducted.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

2.1 Background

According to Okeson (2008), “The (human) masticatory system is the functional unit of the body primarily responsible for chewing, speaking, and swallowing. The system also plays a significant role in tasting and breathing. The masticatory system is made up of bones, joints, ligaments, teeth, and muscles.” The components of the masticatory system can be further grouped into three major skeletal parts (maxilla, mandible and temporal bones) and four pairs of muscles (masseter, temporalis, medial pterygoid and lateral pterygoid) (Fig. 2.1). The maxillary and mandibular dentitions usually contain 28–32 permanent teeth. The anterior maxillary teeth commonly overlap in part with the mandibular teeth, and the overlap is characterized by two parameters (Fig. 2.2): overjet (horizontal overlap) and overbite (vertical overlap).

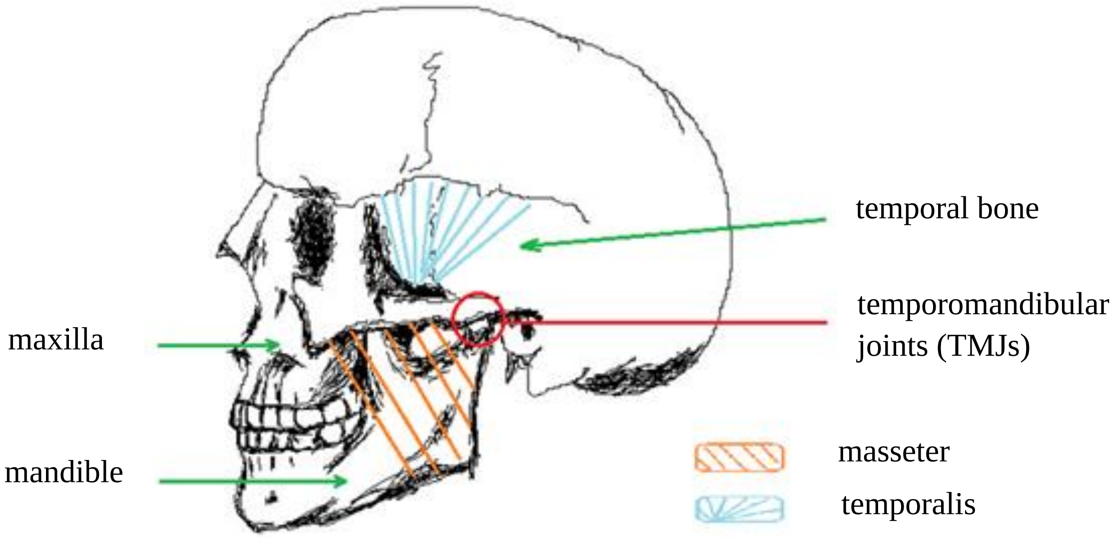

Fig. 2.1. Part of components of masticatory system.

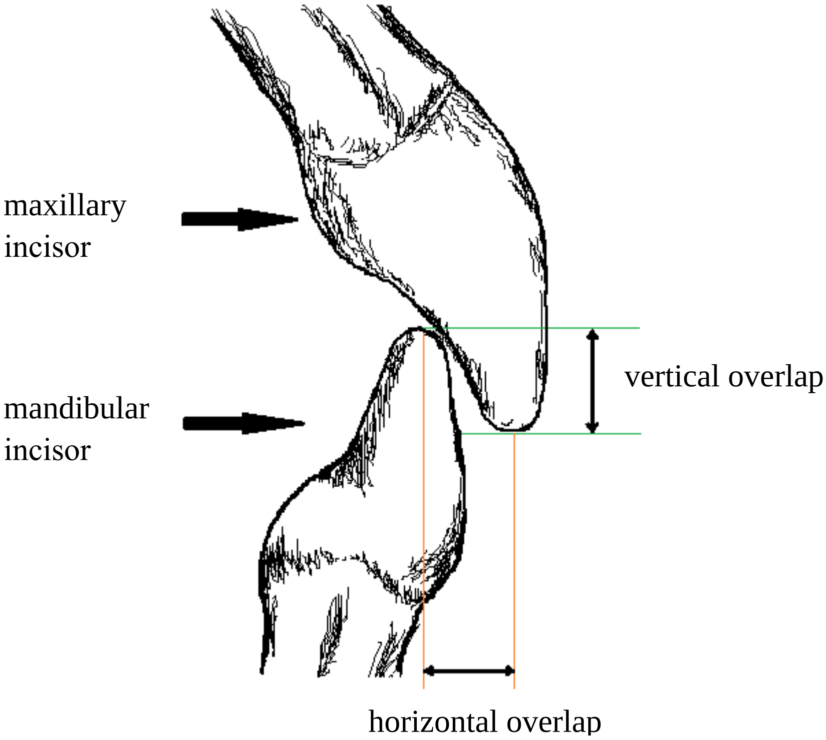

Fig. 2.2. Two types of overlap.
"Reproduced by Ao Sun from Okeson, J. P.: Management of temporomandibular disorders and occlusion (6th edition), Page 73, St. Louis, MO, 2008, Mosby."

Temporomandibular joints (TMJs), one of the most sophisticated joints in human bodies, are formed by the mandibular condyles and the fossae of the temporal bone, with the articular disks separating these two bones (Fig. 2.3). TMJs can fulfill not only a hinging movement but also a gliding movement, so are named ginglymoarthrodial joints (Okeson, 2008). The two projections of the condyle are called lateral and medial poles (LP and MP), and the mediolateral angulations to the transversal direction (∠DMN and ∠DNM, Fig. 2.4) range from 15 to 33 degrees (Gray & Al-Ani, 2011).

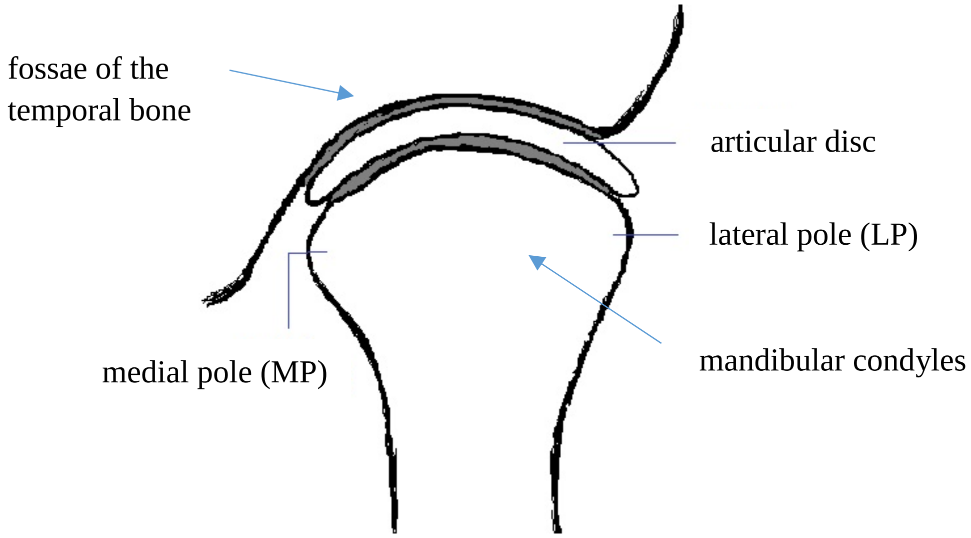

Fig. 2.3. Articular disc, fossa and condyle (anterior view).
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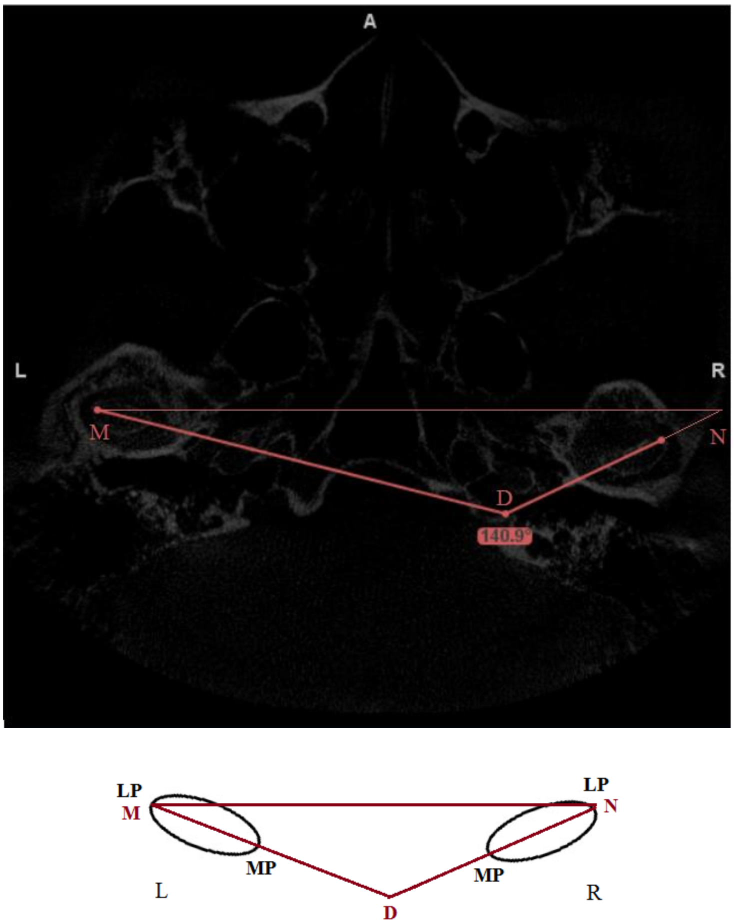


Fig. 2.4. Mediolateral angulation of condyle heads to transversal plane (∠DMN & ∠DNM); angulation of mediolateral axes of the two condyle heads (∠MDN).

2.2 Occlusal Curves

2.2.1 Background

In early dentistry, some specific aspects of dentition were observed. In 1890, F. Graf von Spee illustrated the curve of occlusion after studying skulls with abraded teeth, an observation now defined as the Curve of Spee (Fig. 2.5). According to his description, the curve "begins at the tip of the lower canine, follows the buccal cusps of the natural premolars and molars, and continues to the anterior border of the mandibular ramus" (Curve of Spee, n.d.). In the coronal plane, the Curve of Wilson indicates a curve wherein both the buccal and lingual cusp tips of the posterior teeth on each side of the dental arch make contact and form an imaginary curved line, which is convex in the maxilla and concave in the mandible (Curve of Wilson, n.d.) (Fig. 2.6). Based on these two curves, Monson proposed the concept of Monson's Sphere whereby the mandibular incisal edges, other teeth cusp tips and the centers of the condyles are distributed on a segment of a sphere (Monson, 1932). According to Bonwill's Triangle (Fig. 2.7), when a 4-inch equilateral triangle was formed by the lines between the mesial contact areas of the mandibular central incisors and the centers of the mandibular condyles (Bonwill, 1884), the radius of Monson's sphere was suggested to be 4 inches (Okeson, 2008). Moreover, Monson speculated that in ideal cases, there was a similar sphere formed by the maxillary teeth and the articular surfaces of the fossae (Needles, 1923).

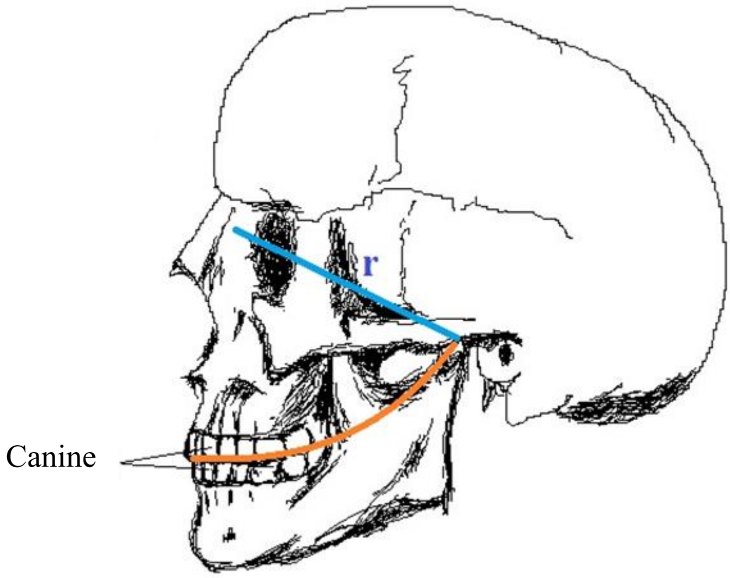


Fig. 2.5. Curve of Spee.

"Reproduced by Ao Sun from Lynch, C. D., & McConnell, R. J. (2002). Prosthodontic management of the curve of Spee: use of the Broadrick flag. *The Journal of prosthetic dentistry*, 87(6), 593–597."

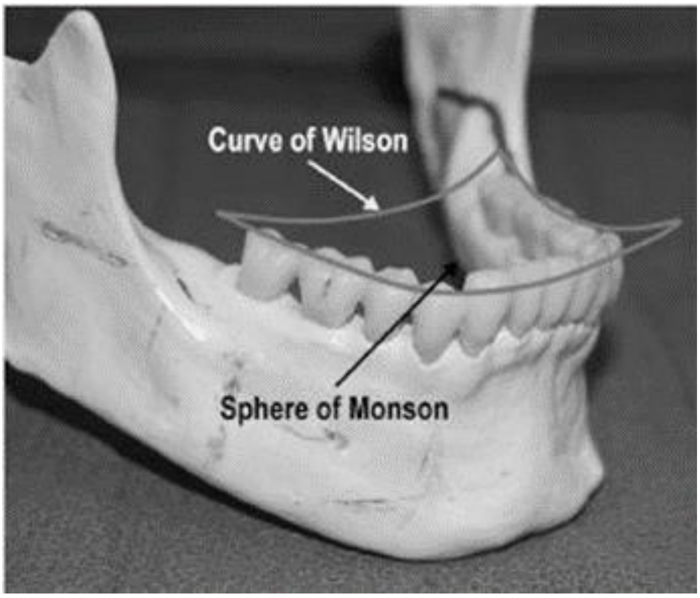


Fig. 2.6. Curve of Wilson and Sphere of Monson (retrieved from www.pocketdentistry.com).

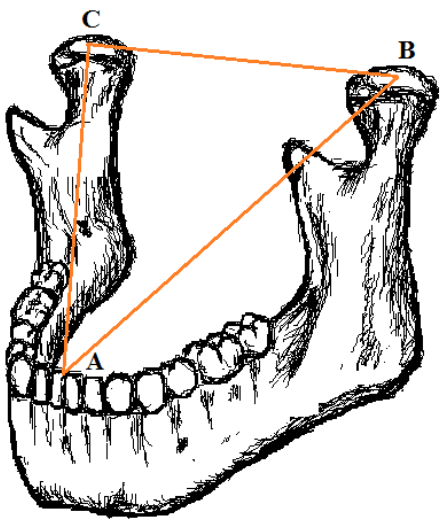


Fig. 2.7. Bonwill's Triangle (△ABC) and Bonwill's Angle (∠BAC).

The concept of occlusal curvature is important in dentistry. In orthodontics, Andrews (1972) proposed that optimal intercuspation depends on a relatively flat occlusal plane, and that leveling the Curve of Spee is a primary goal. The result of leveling the curve was proven to be stable by a post-treatment review (De Praeter, Dermaut, Martens & Kuijpers-Jagtman, 2002). For prosthetic restoration, clinicians are able to reconstruct occlusal curvatures with the help of a flag technique (Broadrick Occlusal Plane Analyzer) (Lynch & McConnel, 2002), or through use of a simplified occlusal plane analyzer (SOPA) that provides a 4-inch radius indicator from the condyle axis of the articulator (Dawson, 2007).

2.2.2 Measurement of Occlusal Curves

Due to important applications in clinical routines, tremendous efforts have been undertaken regarding the study of occlusal curves, including Curve of Spee[1], Curve of Wilson[2] and Monson's Sphere. Ré *et al.* (2008) described that "the mean radius of the curve [of Spee], initially proposed by Spee himself, [in reality] was much lower, 65–70 millimeters in adults.

[1] Also called sagittal occlusal curve.
[2] Also called coronal occlusal curve.

Similar values were obtained by Hitchcock: 69.1 millimeters ± 12.3, and Orthlieb: 83.5 millimeters (standard deviation: 21.3, based on 470 observations).”

Variations of the radii of Monson’s Sphere were also discovered among different ethnic groups. Studies in the literature have shown that in measurements of the models of dentition, Caucasian young adults have an average radius of approximate 101 mm (Ferrario *et al*., 1999), by contrast to 110.6 mm in Japanese young adults (Kagaya *et al*., 2009) and 110.89 mm in Korean young adults (Nam *et al*., 2013).

Christensen (1958) was skeptical about the correctness of the length of each side of Bonwill's Triangle and hence also about the gauge of Monson's Sphere that was based on Bonwill's Triangle. He pointed out that the average measurement of Bonwill's Triangle did not very well match the results he reviewed: for example, only 6% of 300 jaws were in line with the Bonwill’s Triangle figures (Christensen, 1958). Moreover, the intracondylar distance of the mandible could vary considerably between dried mandibles and mandibles first dipped in water for an hour (Christensen, 1958).

2.2.3 Association of Occlusal Curves, Other Dentofacial Attributes and TMJs

There exist some specific relationships between occlusal curves and dentofacial characteristics. The radius of an occlusal curve may have clinical significance as well as some association with other dentofacial attributes.

Xu, Suzuki, Muronoi and Ooya (2004) found that gender had no impact on this curve, which was in agreement with the findings of Ferrario, Sforza and Miani (1997) and Ferrario *et al.* (1999). However, some researchers held the opposite view, arguing that there were gender differences in the occlusal curves, particularly that the sphere radii in males were larger than those in females (Kagaya *et al.*, 2009; Nam *et al*., 2013; Fueki, Yoshida & Igarashi, 2013).

Baydaş *et al.* (2004) recruited 137 untreated subjects, 76 girls and 61 boys aged from 13 to 16 years, and evaluated the cephalometrical films and dental casts of the group who were categorized into three groups in terms of the depth of the Curve of Spee. They found that the variation of the Curve of Spee had a significant impact on overjet and overbite, and that overjet and overbite were significantly larger in the deep Spee group as compared to those in the other two groups. A similar result was obtained by Cheon *et al*. (2008): where overjet and overbite increased, the Curve of Spee became deeper. Farella, Michelotti, Eijden and Martina (2002) noted that when the condyles were situated further posteriorly to the mandibular dentition, or when the sagittal position of the mandible was located more anteriorly to the anterior cranial base (SNB), the radius of the relative Curve of Spee increased.

Veli, Ozturk and Uysal (2015) stated that the depth of the Curve of Spee decreased with respect to the Angle Classification in the following orders: Class II Division 1, Class II Division 2, Class I and Class III malocclusion groups.

Sakaguchi, Uehara, Yagi and Miyawaki (2012) asserted that the masticatory bite force of the study population increased with the growth of the radius of the occlusal sphere formed by the mandibular premolars and molars. Fueki, Yoshida and Igarashi (2013) examined 50 young adults to explore the association between the occlusal curvature and masticatory function. They reached the conclusion that a flatter mandibular curvature (a larger sphere) in the subjects supported better in food comminuting and mixing ability. In addition, while the median of the sphere radius in the male subjects was greater than that in the female group, the difference was not statistically significant.

Although the movement of the mandible is complex, the interactive harmony of the occlusal curves appears to be one of the elementary traits of the masticatory system. With appropriate curvature of the Curve of Spee, protrusive contact of the incisor teeth occurred without interference from the posterior teeth (Needles, 1923). In Japanese adults, the Curve of Spee in mandibular dentition was significantly more squeezed than that in maxillary dentition (Xu, Suzuki, Muronoi & Ooya, 2004). Moreover, by analyzing 46 young adults with complete dentition, Fueki, Yoshida, Okano and Igarashi (2013) revealed that the masticatory movement was significantly impacted by the Monson's Sphere radius, and that flatter occlusal curvatures were suggested to be associated with faster mandible motion and contributed to chewing efficiency; further, there was a significant difference between the gender categories in the sphere radii and the movement parameters.

In order to differentiate occlusal curvatures in people with and without signs and symptoms of Temporomandibular Disorders (TMDs), (a range of conditions affecting the temporomandibular joints, masticatory muscles and contiguous tissues [Manfredini, 2010]), Kanavakis and Mehta investigated 100 subjects (78 female and 22 male) and found that the Curve of Spee of subjects with TMJ sounds were more likely to be flatter than those without TMJ sounds. Ito *et al*. (1997) proposed that the curve of Spee and the curve of Wilson were significantly different between the craniomandibular disorder patients with clicking and locking and the healthy subjects. Ali *et al*. (2003) reported that after analyzing 37 female orthodontic patients, the values of the occlusal curvatures of the specific mandibular teeth differed significantly between the deviated side and the non-deviated side in patients with TMDs. Nevertheless, no significant association of the occlusal curvatures to mandibular deviation was found in the group without TMDs, so the authors proposed that such occlusal curvatures in patients with TMDs might result from compensation to the mandibular deviation.

To sum up, occlusal curves may to a certain extent be a consequence of the chewing performance of the masticatory system, and yet also may be associated with other dentofacial characteristics (this will be discussed later). Further, if form follows function, the margin of diversity in some specific anatomic structures of the masticatory system may partly result from adaption for satisfying the demands of the body under certain other conditions such as food supply, dietary preference, gender difference and so on. However, once the variation of the form exceeds the tolerance limit of the system, detrimental effects that may look like a fatigue effect in engineering may occur in the components of the system.

2.3 Association of Occlusal Features and Temporomandibular Disorders

As a prevalent craniofacial muscloskeletal problem, TMDs affect approximately 5–12% of the population (Facial Pain, n.d.). There are three major groups of TMDs diagnosis: (1) muscle diagnosis, (2) disc displacement and (3) arthritis (Zarb & Carlsson, 1999). Although researchers believed that the etiopathogenesis of TMDs was multifactorial (Seligman & Pullinger, 2000; Chisnoiu *et al*., 2015), the role of the occlusal factors is still unclear and even controversial in relation to TMDs. Hence, a number of studies have probed into the association between occlusal variables and TMDs.

2.3.1 Overjet

Overjet is likely to be prevalently correlated to TMDs. Solberg, Bibb, Nordström and Hansson (1986) reported that excessive overjet was related to TMJ disk replacement. Celić, Jerolimov and Pandurić (2002) evaluated 230 young male adults and found that 38% of the subjects had at least one symptom of TMDs while at least one sign of TMDs occurred in 45% of the subjects, and a weak association between TMD signs and more than 5 mm overjet was drawn by the authors. Kanh *et al.* (1998) investigated 82 asymptomatic volunteers and 263 symptomatic patients, 27 and 221 respectively, with disk displacement, and concluded that patients whose overjet was no less than 4 mm might be at high risk of suffering from TMDs in the future. For those patients, it was necessary to assess other signs of intra-articular TMDs (Kanh *et al.*, 1998). According to Pullinger, Seligman and Gornbein (1993), subjects with more than 4 mm overjet were considered to be vulnerable to Osteoarthrosis and Myalgia Only. In another study, Pullinger and Seligman (2000) confirmed that larger overjet was positively related to the patients with osteoarthrosis. Nevertheless, in a study of 3033 subjects from two population-based cross-sectional studies, John *et al*. (2002) concluded that no association of overbite or overjet with self-reported TMD was detected.

2.3.2 Occlusal Schemes: Contacts and Guidance

Despite the weak association between unilateral temporomandibular disorders and asymmetry in the number of occlusal contacts, Ciancaglini, Gherlone and Radaelli (2003) pointed out that individuals with unilateral TMDs demonstrated relatively greater deviation of contacts between sides. But based on Lauriti *et al*. (2014), the numbers of occlusal contacts had no impact on the three groups that were categorized by the magnitude of TMD (i.e., without TMD, with mild TMD and with moderate to severe TMD).

After examining contact patterns of the mandible laterotrusive-side and mediotrusive-side movements of 240 subjects during sleep, Kawagoe *et al*. (2009) noted that the intensity of mediotrusive side teeth contacts on molar areas during sleep bruxism was suggested to be associated with the signs of TMD, such as clicking and jaw pain. Moreover, the absence of canine guidance on lateral excursion was believed to contribute to the development of TMDs (Selaimen *et al*., 2007). However, Kanh *et al.* (1999) held the opposite opinion from their results, group function guidance was more prevalent on both right and left sides in asymptomatic volunteers with normal TMJs, whereas canine guidance was more prevalent on the right side in the symptomatic group with TMJ disk displacement.

2.3.3 Malocclusion

Selaimen *et al.* (2007) stated that there was correlation between Class II malocclusion and TMDs through the analysis of 72 TMD patients with myofascial pain and 30 individuals without pain. Kanh *et al.* (1999) advocated that Class II Division I malocclusion was more common in the symptomatic group in comparison with the control group. By contrast, Mohlin *et al.* (2007) negated the significant association of specific types of malocclusions to TMDs in a systematic literature review, and they recommended more longitudinal studies on this issue.

2.3.4 Unilateral Posterior Crossbite

According to Pullinger, Seligman and Gornbein (1993), unilateral posterior maxillary lingual crossbite had a 10% overall incidence in the adult subjects studied, and could contribute to the occurrence of TMJ internal derangement. Seligman and Pullinger (2000) reported that the condition of unilateral posterior crossbite in a diagnostic group comprising 124 female patients with intracapsular TMD was significantly distinct from that in the group comprising 47 female asymptomatic control subjects. Pullinger and Seligman in 2000 repeated the positive relation between unilateral posterior crossbite and patients with TMJ disk displacement (Pullinger & Seligman, 2000). To the contrary, however, Farella, Michelotti, Milani and Martina (2007) stated that, based on evidence from 1291 subjects in three schools, TMJ disk displacement in young adolescents was not associated with unilateral posterior crossbite. Apart from unilateral posterior crossbite, Solberg, Bibb, Nordström and Hansson (1986) related partial or total crossbite to increased deviation in form (DIF) of all the TMJ components.

2.3.5 Loss of Posterior Teeth

The loss of posterior teeth appears to be another risk factor for TMDs (Pullinger, Seligman & Gornbein, 1993), with risk compatibility of the TMJs possibly relative to the number of lost posterior teeth (Pullinger & Seligman, 2000). Tallents *et al.* (2002) claimed that the incidence of missing mandibular posterior teeth was higher in the symptomatic TMD patients with disc displacement after estimating 82 asymptomatic volunteers and 263 symptomatic TMD patients. Wang *et al*. (2007) concluded that a loss of posterior teeth contributed to the occurrence of TMD symptoms from a study of 113 patients who had lost posterior teeth, 64 with and 49 without TMD symptoms.

2.3.6 Other Factors

Other factors such as occlusal interference (Clark, Tsukiyama, Baba & Watanabe, 1999), nonworking-side interferences (Celić, Jerolimov & Pandurić, 2002) and longer RCP-ICP slides (Pullinger & Seligman, 2000) were suggested to be the risk factors for TMDs, while Kanh *et al.* (1999) described that more nonworking-side contacts were detected in an asymptomatic volunteer group than in the symptomatic group.

Although most of the findings seem to support the premise that occlusal factors are important risk indicators for the development of TMDs, it was emphasized that there was no simple cause-effect relationship between a single occlusal feature and signs and symptoms of TMDs (Kahn *et al.*, 1999), and that the correlation of occlusal factors to TMDs was not the appropriate determinant for the identification of patients with TMDs (Celić, Jerolimov & Pandurić, 2002).

In addition, neither should the effect of the occlusal features for characterizing patients with TMDs be exaggerated (Pullinger & Seligman, 2000), nor should clinicians conduct occlusal therapy on but a presumption of occlusal cause or without controlling the TMDs symptoms (Seligman & Pullinger, 2000). Some occlusal factors were supposed to be a secondary outcome rather than causative in the occurrence of TMDs, such as anterior open bite or reduced overbite in osteoarthrosis in adults (Pullinger & Seligman, 2000).

2.4 Morphologic Changes of TMJs and Condylar Height

Despite the exclusion of the flattening shape of the condyle head as a determinant sign for diagnosing TMJ osteoarthritis or degenerative joint disease (Ahmad *et al.*, 2009; Schiffman *et al.*, 2014), morphologic analysis of the condyle has become of increasing concern to researchers exploring the correlation of TMDs to occlusal variables. Mongini (1977) stated that remodeling[3] of condyles could result from a functional adaptation of the joint under a new registration of occlusion, and in a specific population might antedate symptoms of a pain-dysfunction syndrome. Zarb and Carlsson (1999) proposed that long-time exposure of the TMJs to functional or parafunctional loading might cause adaptive joint changes and eventually even joint degeneration; moreover, the alternation from adaptive to degenerative osseous changes with symptoms could be induced by certain factors such as genetic predispositions, trauma, dental morphologic defects, etc. On the contrary, however, Dawson (1999) described his perspective in a position paper asserting that lost condylar height led to spontaneous posterior teeth wear. Further, Krisjane *et al.* (2012) mentioned that the changes in occlusion might follow degenerative bony alternation of the condyles.

[3] Bone remodeling: Absorption of bone tissue and simultaneous deposition of new bone; in normal bone the two processes are in dynamic equilibrium. Remodeling, (n.d.), Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health, 7th ed. (2003). Retrieved April 15, 2017, from http://medical-dictionary.thefreedictionary.com/remodeling

Ribeiro *et al*. (2015) exhibited the TMJ shapes in four categories (Fig. 2.8) and reported that in their investigation the rounded condyles were the most prevalent in the lateral and posterior view; however, they found that there existed differences between the shapes of some condyles and the relative fossae. The authors attributed the presence of articulating disks to the role that assists complex movements of TMJs and makes up for the disharmonies of the morphologic variations between the condyles and fossae.

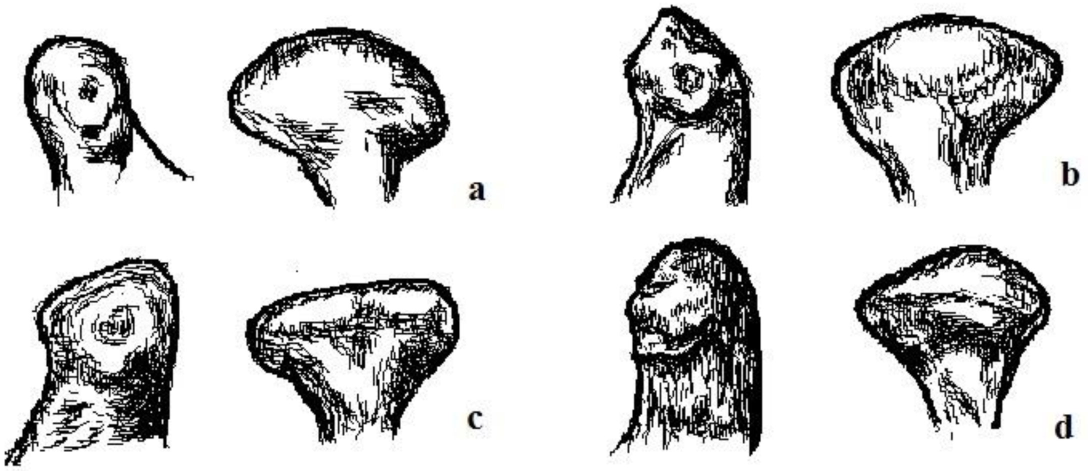


Fig. 2.8. Lateral view and posterior view of shapes of condyle heads
a. rounded, b. angled, c. flattened, d. mixed.
"Reproduced by Ao Sun from Ribeiro, E. C., Sanches, M. L., Alonso, L. G., Smith, R. L., RIBEIRO, E., SANCHES, M. & SMITH, R. (2015). Shape and Symmetry of Human Condyle and Mandibular Fossa. Int. J. Odontostomat, 9(1), 65–72."

By observing 96 isolated left condyles and the relative occlusal conditions, Solberg, Bibb, Nordström and Hansson (1986) proposed that the morphologic changes were related to malocclusion and were influenced by the interaction of malocclusion and age. The subjects with flat condyles from the coronal view showed a higher prevalence of deep overbite. Katsavrias (2006) reported that oval and round contours accounted for almost 90% of the shapes of 94 condyles of 47 subjects with Class II Division 2 malocclusion. With the investigation of the tomograms from 189 patients (109 Class II Division 1, 47 Class II Division

2 and 33 Class III), Katsavrias and Halazonetis (2005) observed that differences of condylar shape occurred between the Class III group and the other two Class II groups, and that the fossa shape was wider and shallower in the Class III groups in comparison to those in the Class II groups. Krisjane *et al*. (2012) explored the degenerative changes of the joint structures with the cone-beam computed tomography images of 45 Class I, 28 Class II and 44 Class III joints of Caucasian patients, and they concluded that erosive changes were more common in the Class II and III populations, with more than 10% incidence in both. Articular surface flattening was the most prevalent feature of the joints in all three groups. They assumed that the occurrence of articular surface flattening and osteophytes resulted either from some degenerative remodeling or from the adaption to functional loading.

Mongini (1980) demonstrated that the occlusal alternations could be the reason for degenerative changes in TMJs, and that occlusal therapy probably could contribute to the reshaping of the condyle through bone remodeling; moreover, flattened condyles due to occlusal variation tended to be reshaped into rounded ones after occlusal therapy. Takayama *et al*. (2008) found that the incidence of bone change in the condyles of the TMD group was higher than that in the dental group (17.7% vs. 11.6%) from an investigation of 570 patients with TMDs and 970 patients without TMDs; furthermore, those bone changes presented differently in each group according to occlusal patterns as classified by the Eichner's Index.

Cevidanes *et al*. (2010) studied the three-dimensional surface models of mandibular condyles generated from cone-beam computerized tomography images of two groups: 29 female patients with osteoarthritic (OA) TMJs and 36 asymptomatic female subjects. They found that 60% of the condyles of the TMJ OA group displayed differing degrees of surface flattening, whereas some degree of condylar flattening occurred in only 15% of the subjects in the other group. In Fig. 2.9, the authors show the degenerative osseous changes of the condyles in a progressively deteriorating way, where the condylar height reduces gradually. Moreover, compared to the control group, specific locations of the condyles with osteoarthritis (such as anterior surface of the lateral pole or the posterior surface of the medial pole) represented the resorption.

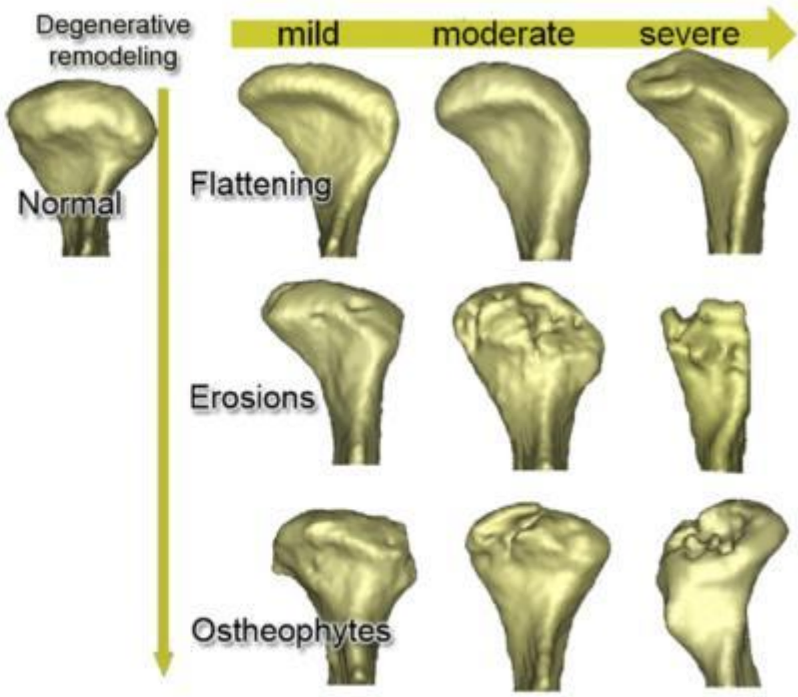


Fig. 2.9. Three-dimensional morphologic distribution of condylar shapes.
"The 3-dimensional morphologic distribution of condylar shapes associated with a possible continuum of osteoarthritic changes. The vertical axis illustrates the progression (flattening, erosions, and osteophytes) of degenerative change, and the horizontal axis illustrates levels of severity. Reprinted from Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology, 110(1), Cevidanes, L. H. S., Hajati, A. K., Paniagua, B., Lim, P. F., Walker, D. G., Palconet, G., ... & Phillips, C., Quantification of condylar resorption in temporomandibular joint osteoarthritis, Page 114, (2010), with permission from Elsevier."

Recently, there has been a trend toward more precise and reasonable quantification of the changes in condyles. The measurement of the condyle height after conservative orthopedic treatment is one of the criteria of the assessment of condylar remodeling. Kinzinger, Kober and Diedrich (2007) introduced a solution for quantifying the morphologic changes in the condyles by using analysis of magnetic resonance imaging (MRI) in order to estimate the prognositic conditions of condyles after fixed orthopedic appliances treatment. In their study, they generally classified three types of the condylar shape in every plane of the axial, frontal and sagittal planes, and they proposed that the frontal and sagittal condylar heights could be measured in the corresponding plane respectively (Fig. 2.10 shows the condylar height in the frontal plane). According to Ma *et al*. (2013), significant growth of condylar height was detected after one year of Andresen Activator appliance therapy in 24 Angle Class II Division I malocclusion teenage patients. In addition, gauging condyle height was also required after TMJ surgery (Ha *et al*., 2013).

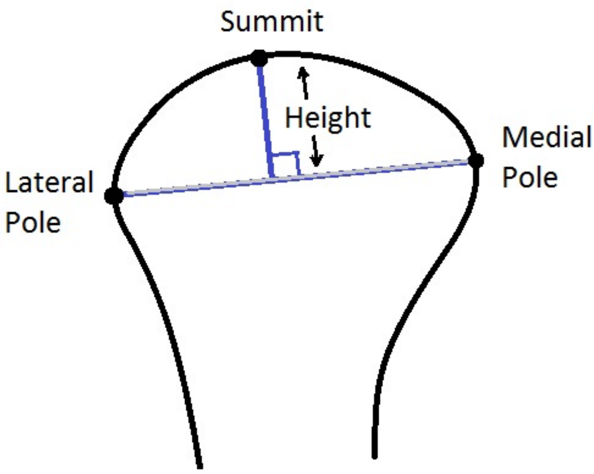


Fig. 2.10. Condylar height in frontal plane.
"adapted from Kinzinger, G., Kober, C., & Diedrich, P. (2007). Topography and morphology of the mandibular condyle during fixed functional orthopedic treatment -- a magnetic resonance imaging study. Journal of Orofacial Orthopedics, 68(2), 124–47."

2.5 Concluding remarks

According to the current literature, measurement of the Curve of Spee is controversial, evaluation of Monson's sphere depends mainly on the models of the teeth, and the authentic position of TMJs is barely involved in the evaluation. In addition, although excessive overjet as well as several other factors are essentially linked to the TMD according to some studies, the association of the morphological characteristics of condyles with the dentofacial attributes is seldom discussed. This thesis attempts to understand a correlation that may exist between Monson's Sphere of both the maxillary and mandibular teeth with respect to TMJs, as well as correlation that may exist between condylar height as a specific aspect of condyles and dentofacial attributes such as discrepancy of the mandibular and maxillary spheres, ANB, Bonwill's Angle, overbite, overjet, the angle of mediolateral axes of two condyles and the distance between the two condyles.

CHAPTER 3 METHODS AND MATERIALS

3.1 Materials

In order to determine the number of subjects that were needed to recruit, a power calculation was performed with G*Power 3.1.9.2.[4] If the correlation between the variables of Condylar Height and Overjet is 0.5,[5] at least 42 subjects are needed with the power over 95%. The database of the CT scanner (GALILEOS Compact, Sirona Dental Systems GmbH, Bensheim, Germany) at the author's previous clinic (Reige Dental Clinic, Shanghai, China) was reviewed, and 54 sets of DICOM data of the Chinese patients were collected. These people came for regular dental care such as extractions and orthodontic, endodontic and/or prosthetic treatment, and were scanned in the maximum intercuspation position. The sample included 43 females and 11 males with ages ranging from 11 to 49 years (Table 3.1).

Table 3.1. Age and gender distribution in the subjects

	Total	Mean	Standard deviation (Std.)	Minimum	Maximum
Male	11	27.1	12.6	12	49
Female	43	28.5	9.6	11	46

3.2 Method

The 3D Resolution (isotropic voxel size) of the GALILEOS Compact was set to be 0.3 mm (Sirona Dental Systems LLC, n. d.), and the exported data were loaded by a DICOM viewer (Mango, University of Texas, USA). The three-dimensional coordinates (in millimeters) of the particular anatomic points and landmarks (Table 3.2) were measured by the author (Figs. 3.1

[4] This is a software program from http://www.gpower.hhu.de/en.html, released on 28 March 2014.
[5] There are three effect size conventions recommended: 0.1 (small), 0.3 (medium), 0.5 (large).

and 3.2), as were the counterparts of the fixed prosthetic restorations. However, few anatomical points (1 lateral pole and 3 summits of the condylar heads of three patients) were not measured due to the limit of the field of view of the CT scanning; thus, these were estimated by the author based on the measurable neighboring anatomical structures.

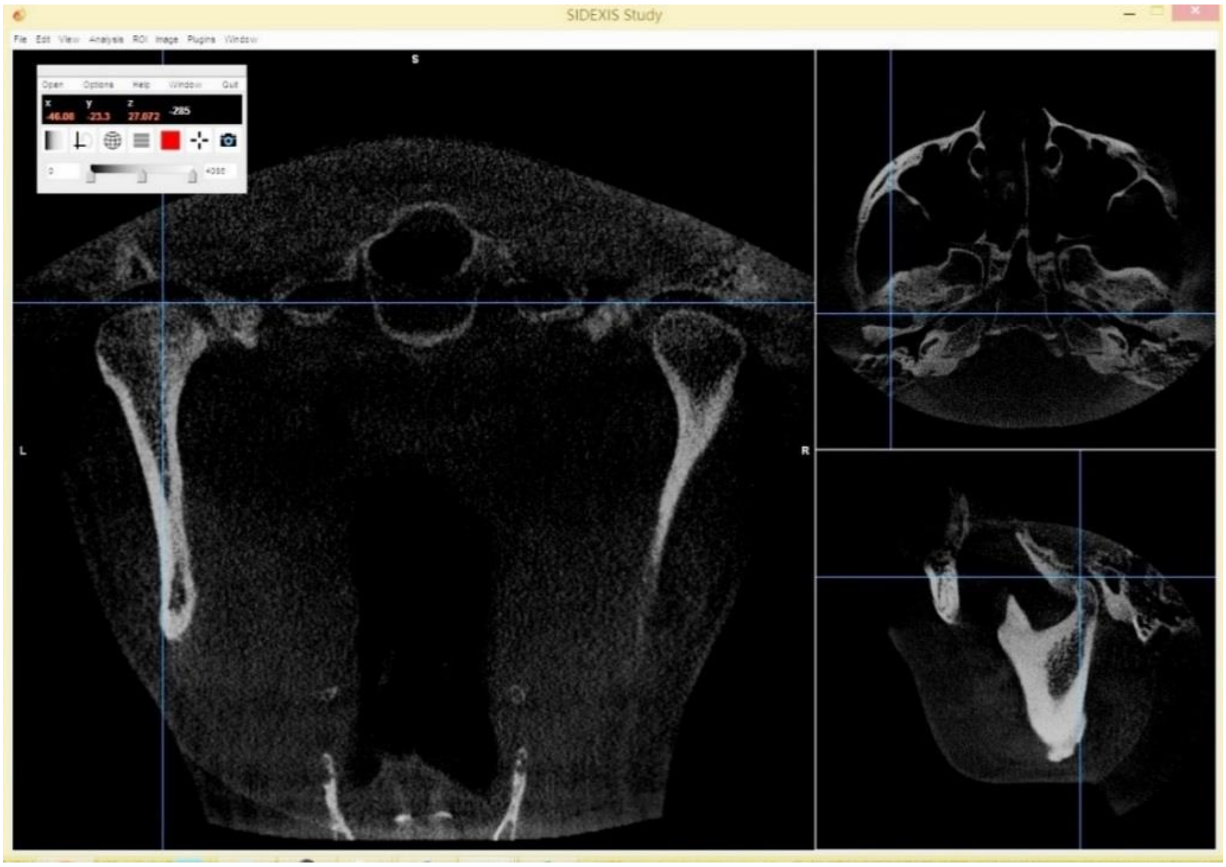


Fig. 3.1. Summit of left condyle
(DICOM software: Mango, University of Texas, USA).

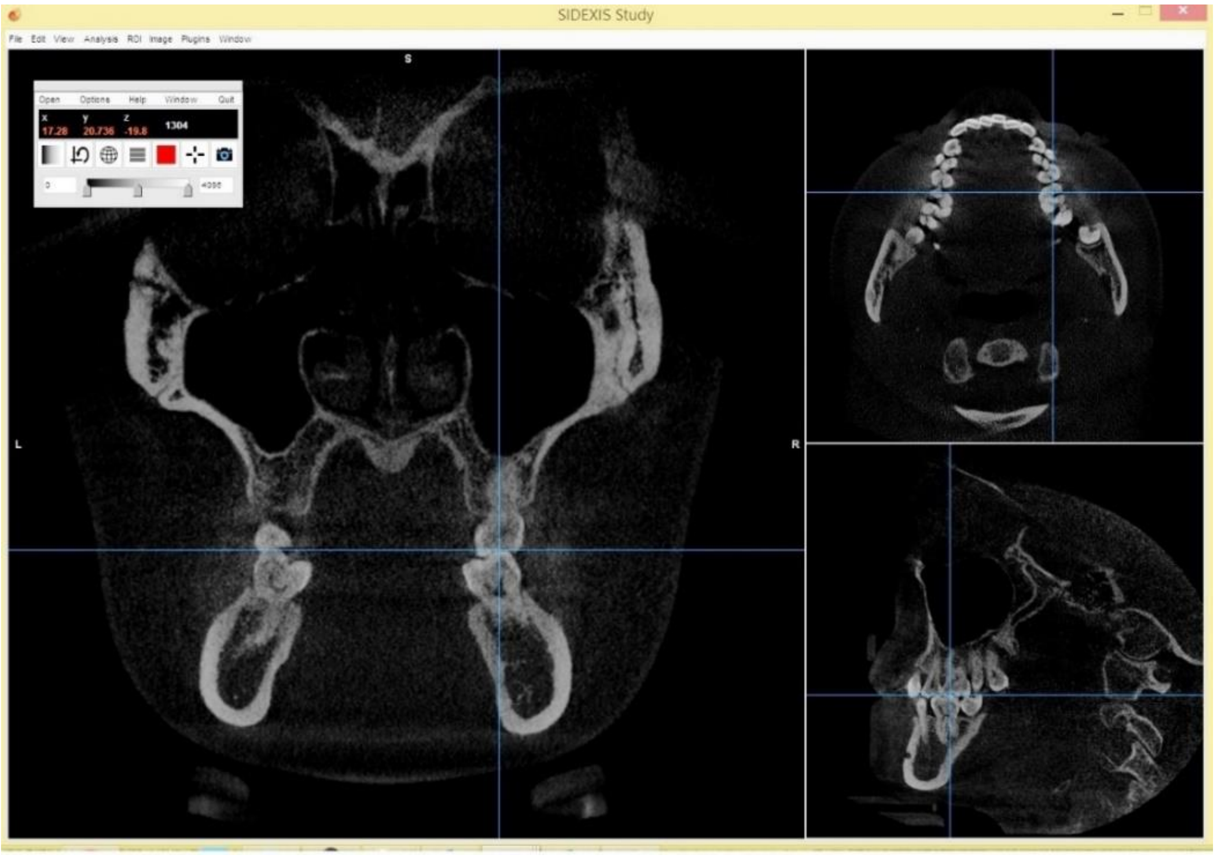


Fig. 3.2. Tip of second buccal cusp of mandibular right first molar (DICOM software: Mango, University of Texas, USA).

Table 3.2. Anatomic landmarks and reference points

Teeth	Mid-points of incisor edges
	Cusp tips of canines
	Buccal cusp tips of mandibular premolars
	Buccal and lingual cusp tips of maxillary premolars
	Buccal and lingual cusp tips of molars
	Normal contacts of third molars
TMJs	Summit of condylar head
	Mid-point of lateral pole
	Mid-point of medial pole
Craniofacial skeleton	Point S, Mid-point of anterior border of sella turcica
	Point N, Nasion
	Point A, most concave point of anterior maxilla
	Point B, most concave point on mandibular symphysis

3.3 Inclusion and Exclusion Criteria

3.3.1 Inclusion Criteria

- For adults, at least one each of molar, premolar and incisor in each quadrant, and no fewer than 10 teeth in each dental arch; for adolescents, at least one permanent molar and one permanent incisor in each quadrant.
- Patients were scanned with the jaws in intercuspal position.

3.3.2 Exclusion Criteria

- Patients who were then receiving orthodontic treatment.
- Patients with 3 landmarks in one condylar head located out of the field of view of the CT scanning.

3.4 Ethical Issues and Bio-REB Approval

The patients signed consent forms before undergoing the CT scanning at the dental clinic, and as well the collection of the CT data was approved by the clinic. Since the research (gathering of CT data) was purely observational, there was no treatment or procedure performed on the patients; the data collection was in line with the Bio-REB regulations, and no personal information could be identified through the research. Additionally, the present study was approved by the Biomedical Research Ethics Board of the University of Saskatchewan (Bio# 16–53; see Appendix A).

3.5 Measurement of Factors

- Overjet

The average of the horizontal distances between the mid-points of the two maxillary central incisor edges and the mandibular incisors, measured in millimeters and in sagittal slices in Mango.

- Overbite

The average of the vertical distances between the mid-points of the two maxillary central incisor edges and the mandibular incisor edges, measured in millimeters and in sagittal slices in Mango.

- Bonwill's Angle (B-Angle)

The angulation formed by the line between the summit of one condyle and the mid-point of the mandibular central incisors and the counterpart on the other side, calculated by the coordinates of the three points (∠BAC in Fig. 2.7).

- Angulation of the mediolateral axes of the two TMJs (M-Angle):

The angulation (∠MDN in Fig. 2.4) formed by the auxiliary lines extending from the mediolateral axes of the two condylar heads, measured in appropriate horizontal slices in Mango.

- Condylar height in the frontal plane **(Condylar Height)**

The average height of the two condylar heads, each height representing the distance from the summit of the condyle to the line between the mid-points of the medial and lateral poles of the condyle (Fig. 2.10), calculated with the coordinates of the three points in millimeters.

- Angle ANB **(**ANB**)** (skeletal relationship)

The angulation formed by the two lines connecting three landmarks (N, A and B, Table 3. 2); the value of Angle SNB subtracted from the value of Angle SNA in this study. Angle SNA and SNB were calculated with the coordinates of the points S, N, A and S, N, B respectively. The standard value (mean ± standard deviation) of ANB in Steiner analysis (Atit *et al.*, 2013) is $2^o \pm 2^o$, so usually people can be categorized into three groups with two values, 0^o and 4^o, as the demarcation: Class I, ANB $<4^o$ & $>0^o$; Class II, ANB $>4^o$; and Class III, ANB $<0^o$. In the tables of statistics analysis of this study, the variable 'ANB' indicates the ANB values of the subjects, and the variable 'Steiner ANB' indicates the levels of Steiner ANB Classification as a fixed factor.

- Ratio of mandibular radii to maxillary radii

The ratio of the mandibular radii to that of the maxillary radii, abbreviated to RMM, is the value of the mandibular radius divided by the relative maxillary one, and is used to represent the discrepancy in the two radii of the subjects.

- Distance between the two summits of the condylar heads

The distance between the two summits of the condylar heads, abbreviated to DisCH, was calculated by the coordinates of the two points in millimeters.

- Radii of the Monson's Sphere in maxilla and mandible (data fitting for the sphere)

With the assumption that the mandibular incisal edges, other teeth cusp tips and the centers of the condyles (in this study, the summit of the condyle substituting for the center of the condyle) are distributed on a segment of the surface of a sphere, Monson's Sphere can be modeled as follows:

$$(x - a)^2 + (y - b)^2 + (z - c)^2 = R^2 \tag{3.1}$$

where a, b, c are the coordinates of the expected center of the sphere, R is the sphere radius and x, y, z are the coordinates of the relative identified points from the DICOM data. The above formula thereby can be transformed as follows:

$$z = -\frac{a}{c}x - \frac{b}{c}y + \frac{1}{2c}(x^2 + y^2 + z^2) + \frac{a^2 + b^2 + c^2 - R^2}{2c} \tag{3.2}$$

Thus, z is taken as the dependent variable and x, y and the summation of x^2, y^2 and z^2 as the independent variables. Data fitting can be performed with SPSS (version 19) via linear regression, so a, b, c and R can be calculated after working out the coefficients and the constant. In addition, the maxillary sphere, like the mandibular one, can also be calculated using the relative coordinates of the maxillary teeth and the summits of the condylar heads.

3.6 Data Analysis

- The radii of the Monson's Sphere were carried out by utilizing the linear regression model.
- The frequency histograms and Q-Q plots demonstrate the frequency distribution of the variables of the subjects and normal curve.
- Pearson Correlation was used to explore the linear correlation of any two factors comprising all as well the variables, and whether the correlation was positive or negative.
- To detect whether there was difference among the Radii of Monson's Sphere grouped by factors such as gender, age and Steiner ANB, and whether multiple factors carried the influence or interaction on one specific variable, the univariate Analysis of Variance (ANOVA) of a general linear model was performed. MANOVA was used to detect whether the multiple variables, as a unit, were influenced by a/some specific fixed factor(s).
- The variables that might have influence on Condylar Height were used as the independent variables in a linear regression, where Condylar Height acted as the dependent variable. The insignificant variables were sifted out after the process. Several other linear relationships between two variables were confirmed and visualized via the linear regression model.
- All the statistical analyses were implemented with SPSS (version 19). Statistical significance (Sig.) was determined by a value of less than 0.05 (0.05 level); in addition, the outcome of Pearson Correlation included both level 0.05 and level 0.01.

- The 3D-scatter diagram generated at www.plot.ly demonstrated the profile of the relationship among Condylar Height and other three dentofacial characteristics (Overjet, Overbite and RMM) in further/additional dimensions.

CHAPTER 4 RESULTS

In the present study, the 54 subjects who met the criteria (see section 3.2) were selected from a database that contained tens of hundreds of cases. The sample population (Table 3.1) comprised 43 female patients aged from 11 to 46 years (mean 28.5, Std. 9.6) and 11 male patients aged from 12 to 49 years (mean 27.1, Std. 12.6). Grouped by age, the population consisted of 14 teenagers and 40 adults.

Table 4.1. Linear regression result of 1 subject with minimum R^2 value out of 54 subjects

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.961	.924	.917	2.14419

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1891.620	3	630.540	137.147	.000
	Residual	156.316	34	4.598		
	Total	2047.937	37			

4.1 Monson's Sphere

Table 4.1 illustrates the result of the linear regression of one of the study subjects with the minimum R^2 value of the population. The Sig. value (close to 0) and the R square value (close to 1) indicate that the identified coordinates fit the linear model (3.2) well. Similarly, the overview of the value of R^2 as listed in Table 4.2 and all the Sig. values of the linear regression results of the other 53 subjects are the same (0.000). The mean radius of the maxillary sphere of all 54 subjects is 92.42 mm, and 85.69 mm in the mandible (Table 4.2). For every subject, the standard deviation of the distance between the identified points to the expected center of the sphere (DIPECS) represents how closely the identified points are scattered across the space of the imaginary sphere surface: the smaller the standard deviation of DIPECS, the more closely all the identified points of a subject generally locate around the surface of the sphere. In the studied population, the standard deviation of the DIPECS in the maxilla range from 0.62 mm to 1.85 mm, and from 0.38 mm to 1.31 mm in the mandible (Table 4.2), which suggests that the mandibular teeth and the condyles are distributed more closely across/on the imaginary sphere surface.

Table 4.2. Results of data fitting of sphere

		Mean	Minimum	Maximum
Maxillary	R^2 of linear regression	0.98	0.924	0.998
	radius (mm)	92.42	73.81	116.54
	Std. of DIPECS (mm)	0.99	0.62	1.85
Mandibular	R^2 of linear regression	0.99	0.963	0.999
	radius (mm)	85.69	71.95	101.41
	Std. of DIPECS (mm)	0.85	0.38	1.31

R^2: coefficient determination.
DIPECS: Distance between identified points to expected center of sphere.

The values of both radii are roughly in normal distribution (Fig. 4.1 and 4.2), and the maxillary seems better normalized than the mandibular. The mean maxillary radius is 97.25 mm in males and 91.19 mm in females, while the mean mandibular radius is 88.94 mm in males and 84.86 mm in females (Table 4.3). The mean radius 94.57 mm is seen in maxillae and 85.91 mm in mandibles of the teenagers, and the adults show 91.67 mm (Table 4.4) mean radius in maxilla and 85.61 mm in mandible. The maxillary radii are significantly greater than those in the mandible (mean/maxilla 92.42 mm, mean/mandible 85.69 mm [Table 4.3]; Sig. value: 0.000

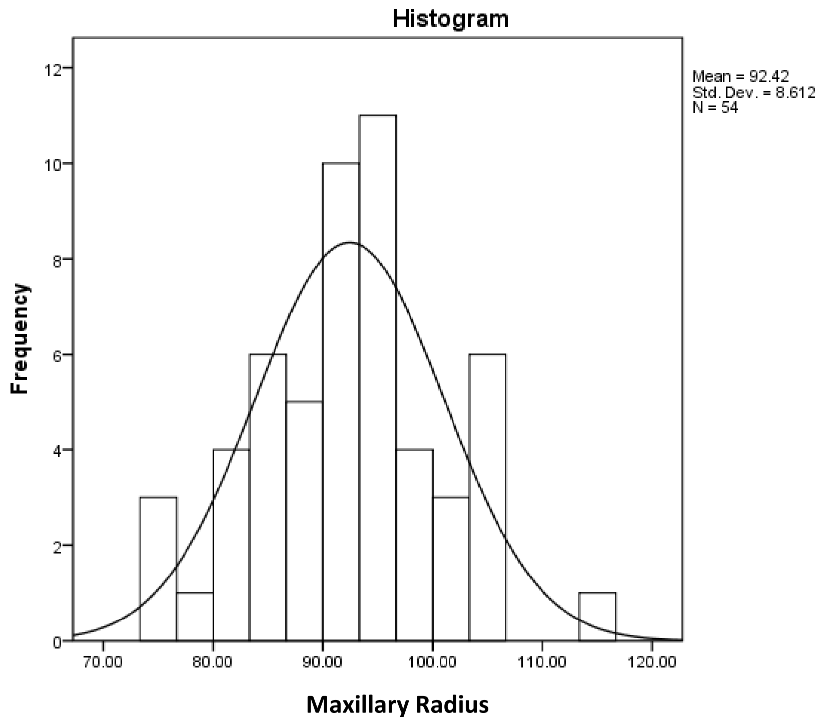
[Table 4.5]). Regarding the influence of gender and age on the radii of the 54 subjects, gender has a significant impact only on the maxillary radii (Sig. Value 0.044 [Table 4.6; Table 4.7]), whereas age has no impact on the radii of both dentitions (Tables 4.6 and 4.7). According to Pearson Correlation (Table 4.9), Maxillary Radius shows a positive moderate correlation to Overjet, Overbite and ANB, whereas Mandibular Radius is weakly correlated only to ANB. The linear regression models of the maxillary and mandibular radii to Overjet and Overbite are displayed in Figs. 4.3, 4.4, 4.5 and 4.6, and only Maxillary Radius has a significant linear relationship with Overjet and Overbite. Under multivariate analysis, where the two radii are both dependent variables, Steiner ANB has a significant influence on the two radii when they are taken as one unit (Sig. 0.002 [Table 4.8]); however, difference occurs only in the Maxillary Radius grouped by Steiner ANB with the univariate ANOVA (Table 4.10). The overview of the dentofacial characteristics and TMJ features can be found in Table 4.11.

Table 4.3. Distribution of radii grouped by gender

	Gender	N	Mean (mm)	Std. (mm)	Minimum	Maximum
Maxillary Radii	M	11	97.25	8.74	88.37	116.54
	F	43	91.19	8.23	73.81	105.94
	Total	54	92.42	8.61	73.81	116.54
Mandibular Radii	M	11	88.94	7.69	81.25	101.41
	F	43	84.86	7.55	71.95	101.36
	Total	54	85.69	7.69	71.95	101.41

Table 4.4. Distribution of radii grouped by age

Age		N	Mean (mm)	Std.	Minimum	Maximum
<20 years	Maxillary	14	94.57	8.34	81.76	105.35
	Mandibular		85.91	7.37	75.72	97.35
>= 20 years	Maxillary	40	91.67	8.68	73.81	116.54
	Mandibular		85.61	7.89	71.95	101.41



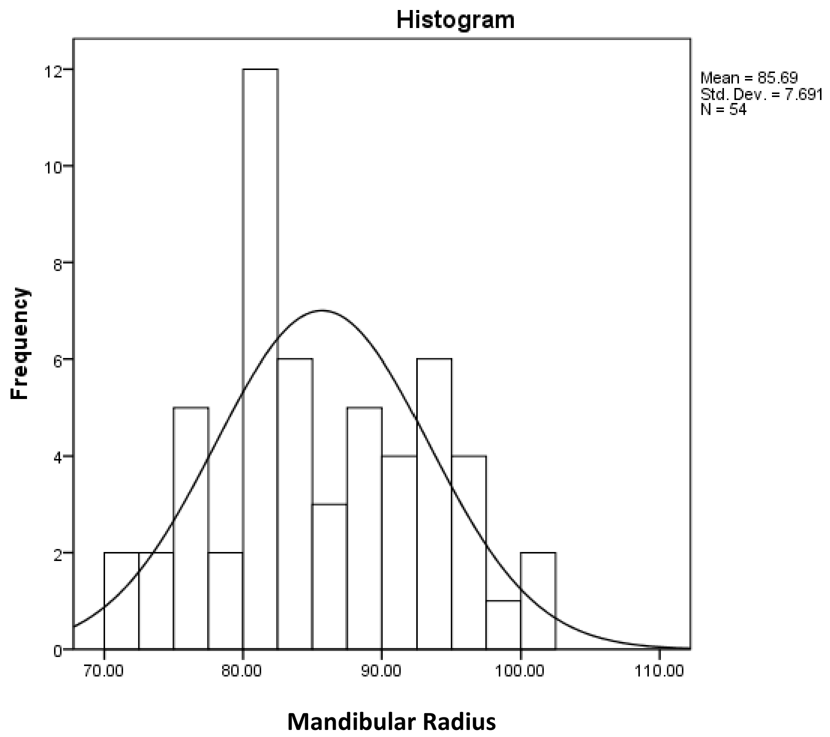
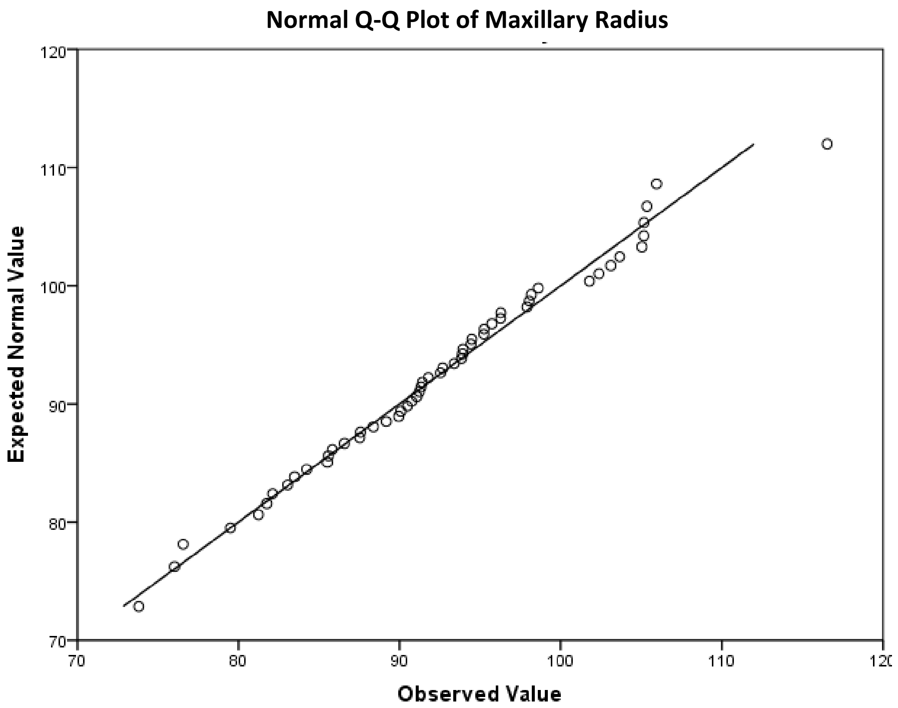


Fig. 4.1. Frequency distribution of Maxillary Radius and Mandibular Radius.



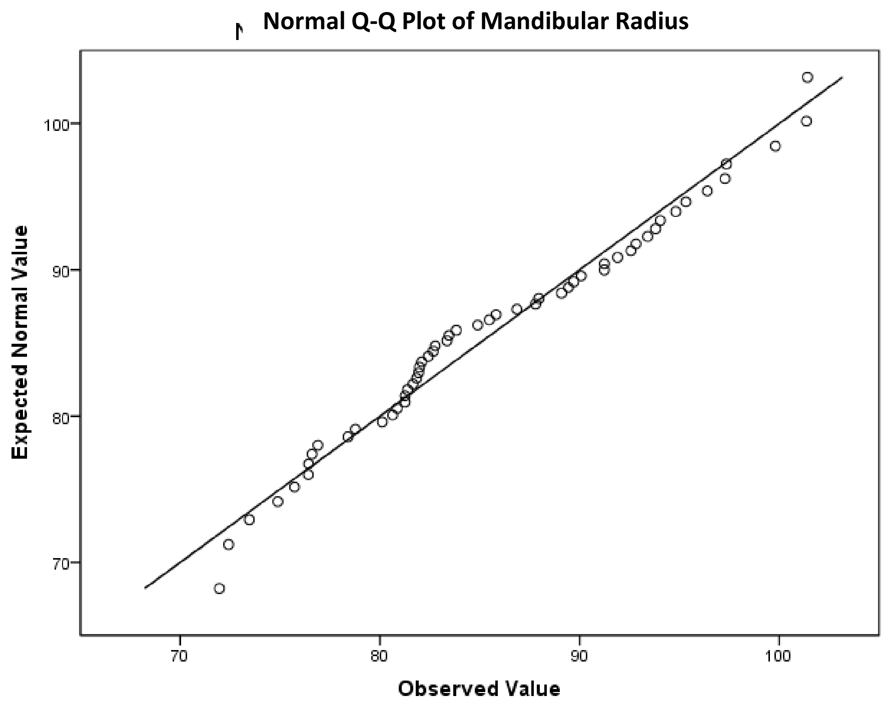


Fig. 4.2. Q-Q Plot of Maxillary Radius and Mandibular Radius.

Table 4.5. Difference between maxillary and mandibular radii

Tests of Between-Subjects Effects

Dependent Variable: Radii

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1223.918	1	1223.918	18.359	.000
Intercept	856552.363	1	856552.363	12848.178	.000
Side	1223.918	1	1223.918	18.359	.000
Error	7066.726	106	66.667		
Total	864843.007	108			
Corrected Total	8290.644	107			

Table 4.6. Influence of gender and age on maxillary radii

Tests of Between-Subjects Effects

Dependent Variable: Maxillary Radius

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	392.074	3	130.691	1.847	.151
Intercept	274446.048	1	274446.048	3878.102	.000
Gender	301.889	1	301.889	4.266	.044
Age	69.637	1	69.637	.984	.326
Gender * Age	17.563	1	17.563	.248	.621
Error	3538.407	50	70.768		
Total	465188.538	54			
Corrected Total	3930.480	53			

Table 4.7. Influence of gender and age on mandibular radii

Tests of Between-Subjects Effects

Dependent Variable: Mandibular Radius

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	149.267[a]	3	49.756	.833	.482
Intercept	230907.807	1	230907.807	3866.980	.000
Gender	142.510	1	142.510	2.387	.129
Age	.215	1	.215	.004	.952
Gender * Age	3.117	1	3.117	.052	.820
Error	2985.635	50	59.713		
Total	399645.531	54			
Corrected Total	3134.902	53			

Table 4.8. MANOVA of Maxillary Radius and Mandibular Radius with Steiner ANB as fixed factor

Multivariate Tests

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.991	2750.935	2	50	.000
	Wilks' Lambda	.009	2750.935	2	50	.000
	Hotelling's Trace	110.037	2750.935	2	50	.000
	Roy's Largest Root	110.037	2750.935	2	50	.000
Steiner ANB	Pillai's Trace	.277	4.100	4	102	.004
	Wilks' Lambda	.724	4.382	4	100	.003
	Hotelling's Trace	.380	4.654	4	98	.002
	Roy's Largest Root	.376	9.597	2	51	.000

Table 4.9. Pearson Correlation of all variables

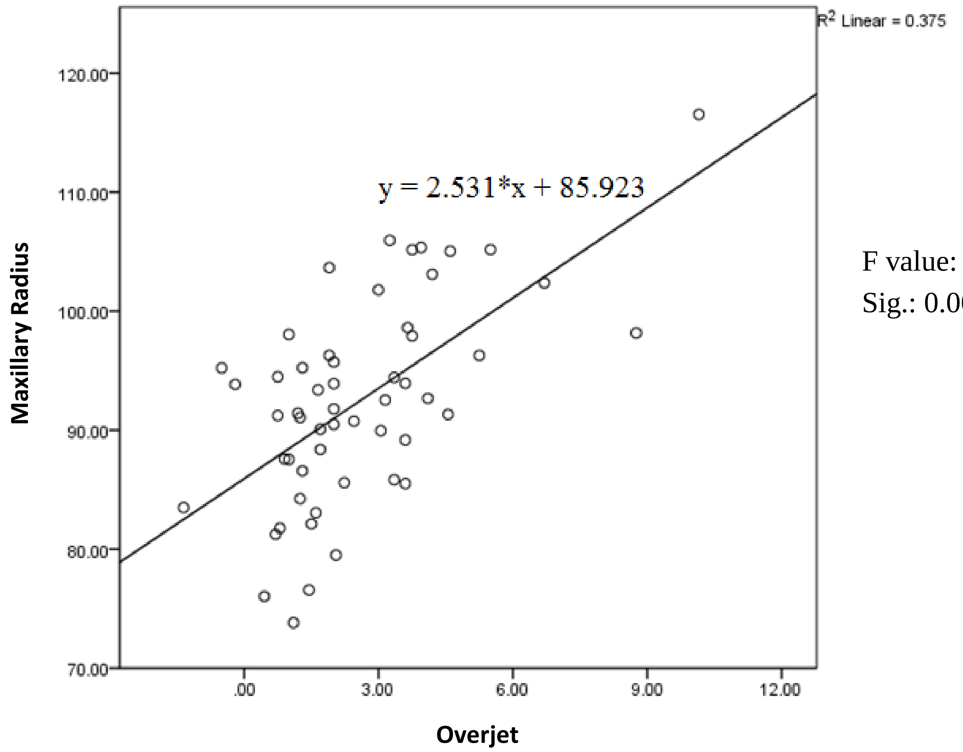
		Maxillary Radius	Mandibular Radius	M-Angle	B-Angle	ANB
Maxillary Radius	Pearson Correlation	1	.665**	-.275*	.087	.586**
	Sig. (2-tailed)		.000	.044	.532	.000
	N	54	54	54	54	54
Mandibular Radius	Pearson Correlation	.665**	1	-.062	-.205	.344*
	Sig. (2-tailed)	.000		.657	.136	.011
	N	54	54	54	54	54
M-Angle	Pearson Correlation	-.275*	-.062	1	-.352**	-.377**
	Sig. (2-tailed)	.044	.657		.009	.005
	N	54	54	54	54	54
B-Angle	Pearson Correlation	.087	-.205	-.352**	1	.330*
	Sig. (2-tailed)	.532	.136	.009		.015
	N	54	54	54	54	54
ANB	Pearson Correlation	.586**	.344*	-.377**	.330*	1
	Sig. (2-tailed)	.000	.011	.005	.015	
	N	54	54	54	54	54
Overjet	Pearson Correlation	.612**	.125	-.468**	.314*	.575**
	Sig. (2-tailed)	.000	.366	.000	.021	.000
	N	54	54	54	54	54
Overbite	Pearson Correlation	.413**	-.247	-.255	.480**	.457**
	Sig. (2-tailed)	.002	.072	.063	.000	.001
	N	54	54	54	54	54
Condylar Height	Pearson Correlation	-.376**	-.186	.487**	-.454**	-.402**
	Sig. (2-tailed)	.005	.178	.000	.001	.003
	N	54	54	54	54	54
DisCH	Pearson Correlation	.226	.310*	-.080	.443**	.211
	Sig. (2-tailed)	.100	.023	.564	.001	.125
	N	54	54	54	54	54
RMM	Pearson Correlation	-.440**	.376**	.260	-.344*	-.321*
	Sig. (2-tailed)	.001	.005	.058	.011	.018
	N	54	54	54	54	54

continued

		Overjet	Overbite	Condylar Height	DisCH	RMM
Maxillary Radius	Pearson Correlation	.612**	.413**	-.376**	.226	-.440**
	Sig. (2-tailed)	.000	.002	.005	.100	.001
	N	54	54	54	54	54
Mandibular Radius	Pearson Correlation	.125	-.247	-.186	.310*	.376**
	Sig. (2-tailed)	.366	.072	.178	.023	.005
	N	54	54	54	54	54
M-Angle	Pearson Correlation	-.468**	-.255	.487**	-.080	.260
	Sig. (2-tailed)	.000	.063	.000	.564	.058
	N	54	54	54	54	54
B-Angle	Pearson Correlation	.314*	.480**	-.454**	.443**	-.344*
	Sig. (2-tailed)	.021	.000	.001	.001	.011
	N	54	54	54	54	54
ANB	Pearson Correlation	.575**	.457**	-.402**	.211	-.321*
	Sig. (2-tailed)	.000	.001	.003	.125	.018
	N	54	54	54	54	54
Overjet	Pearson Correlation	1	.640**	-.343*	.162	-.588**
	Sig. (2-tailed)		.000	.011	.241	.000
	N	54	54	54	54	54
Overbite	Pearson Correlation	.640**	1	-.276*	.043	-.796**
	Sig. (2-tailed)	.000		.043	.755	.000
	N	54	54	54	54	54
Condylar Height	Pearson Correlation	-.343*	-.276*	1	.059	.237
	Sig. (2-tailed)	.011	.043		.672	.084
	N	54	54	54	54	54
DisCH	Pearson Correlation	.162	.043	.059	1	.102
	Sig. (2-tailed)	.241	.755	.672		.465
	N	54	54	54	54	54
RMM	Pearson Correlation	-.588**	-.796**	.237	.102	1
	Sig. (2-tailed)	.000	.000	.084	.465	
	N	54	54	54	54	54

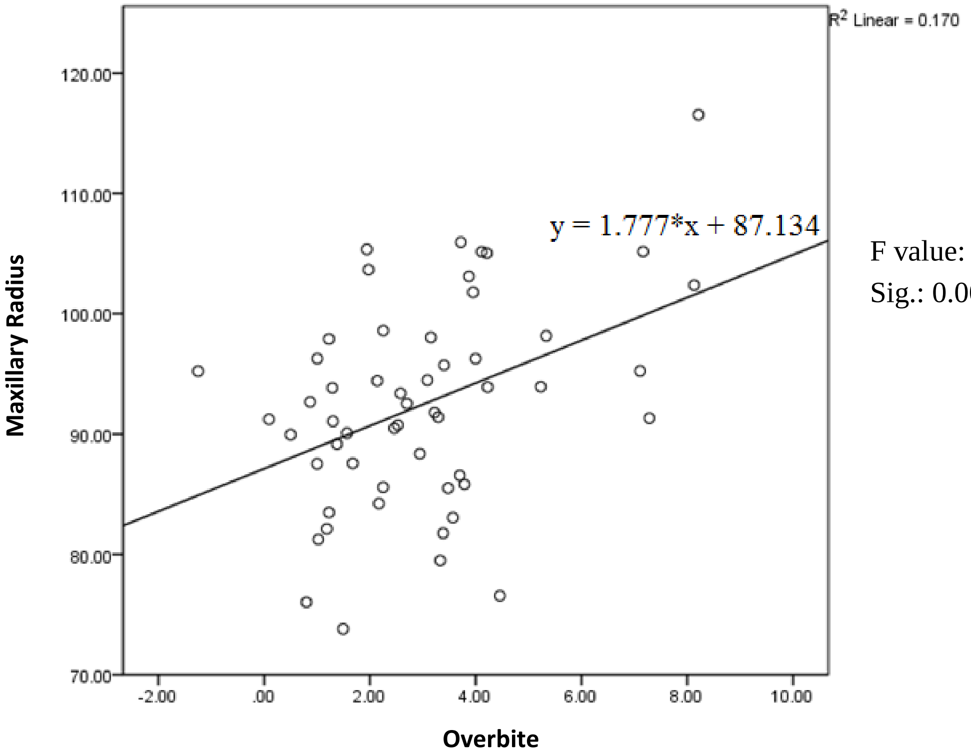
**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



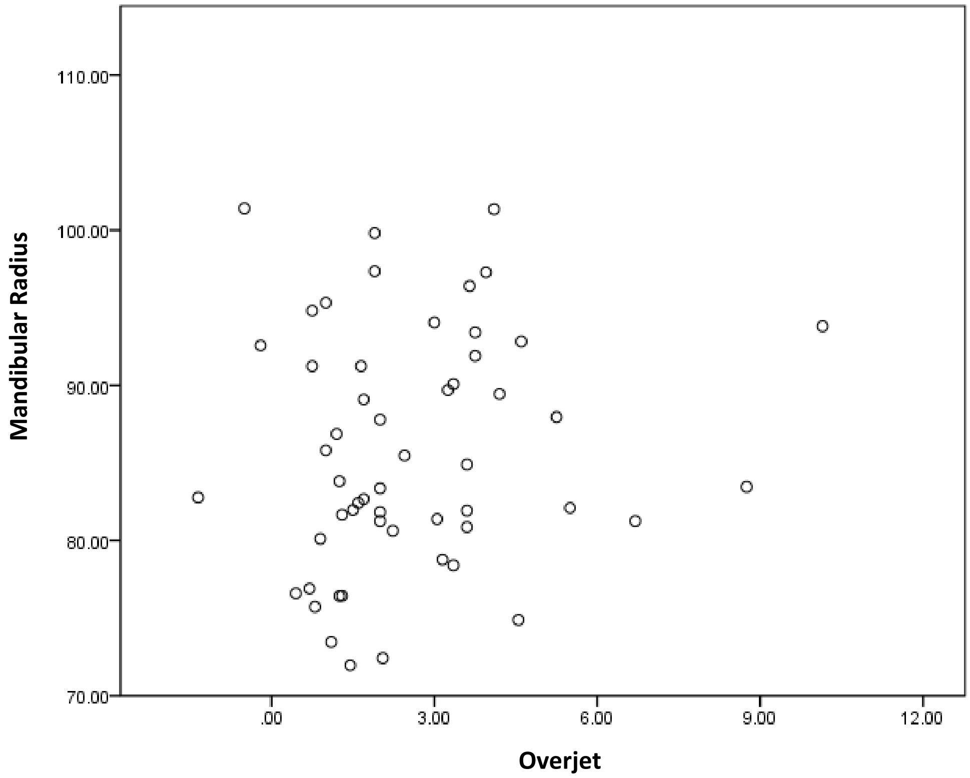
F value: 31.155
Sig.: 0.000

Fig. 4.3. Linear regression of Maxillary Radii and Overjet.



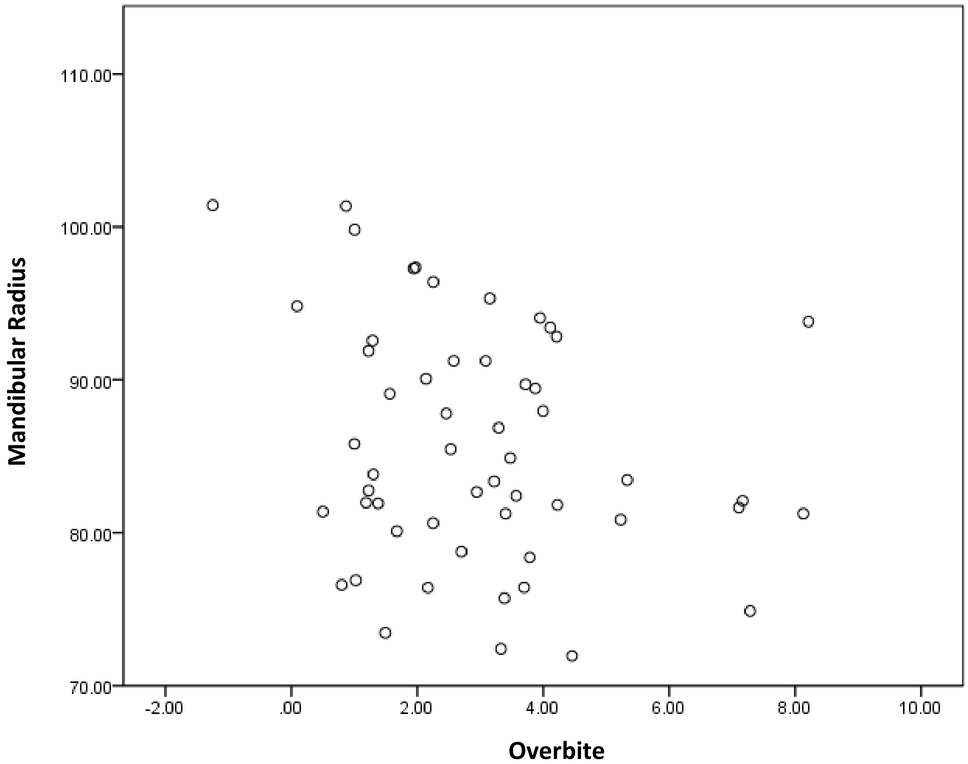
F value: 10.664
Sig.: 0.002

Fig. 4.4. Linear regression of Maxillary Radius and Overbite.



F value: 0.83
Sig.: 0.366

Fig. 4.5. No linear relationship between Mandibular Radius and Overjet.



F value: 3.38
Sig.: 0.072

Fig. 4.6. No significant linear relationship between Mandibular Radius and Overbite.

Table 4.10. Univariate ANOVA of Maxillary Radius and Mandibular Radius with Steiner ANB as fixed factor

Tests of Between-Subjects Effects						
Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Maxillary Radius	1046.772	2	523.386	9.256	.000
	Mandibular Radius	252.890	2	126.445	2.238	.117
Intercept	Maxillary Radius	273397.007	1	273397.007	4835.179	.000
	Mandibular Radius	243155.232	1	243155.232	4302.869	.000
Steiner ANB	Maxillary Radius	1046.772	2	523.386	9.256	.000
	Mandibular Radius	252.890	2	126.445	2.238	.117
Error	Maxillary Radius	2883.709	51	56.543		
	Mandibular Radius	2882.011	51	56.510		
Total	Maxillary Radius	465188.538	54			
	Mandibular Radius	399645.531	54			
Corrected Total	Maxillary Radius	3930.480	53			
	Mandibular Radius	3134.902	53			

Table 4.11. Overview of eight variables

	N	Mean	Std.	Minimum	Maximum
M-Angle (degree)	54	139.6	16.4	93	179
B-Angle (degree)	54	58.7	3.5	51.4	66.3
ANB (degree)	54	4.1	3.1	-3.2	12.5
Overjet (mm)	54	2.6	2.1	-1.4	10.2
Overbite (mm)	54	3	2	-1.2	8.2
Condylar Height (mm)	54	5.9	1.3	3.3	8.6
RMM	54	0.93	0.067	0.781	1.094
DisCH(mm)	54	100.87	4.2	92	112.39

4.2 Ratio of Mandibular Radii to Maxillary Radii (RMM)

The results of RMM are also close to the normal distribution (Fig. 4.7). Table 4.12 shows that the sizes of the maxillary and mandibular radii are close to each other (RMM = 0.978) in the subjects of skeletal Class III, while the greatest deviation in the radii (RMM = 0.915) of the two dentitions occurs in the skeletal Class II population. As well, the skeletal Class I group exhibits a moderate difference between the two radii. Furthermore, while the Steiner ANB classification has some impact on RMM, it is not significant (Sig. value: 0.06, Table 4.13). There is a strong negative relationship between RMM and Overbite (r = -0.796, Sig. value: 0.000, Table 4.9), and RMM is moderately associated with Overjet in the same way. Figs. 4.8 and 4.9 illustrate the linear relationships between RMM and Overjet/Overbite, and both relationships are significant.

Table 4.12. Distribution of average radii and RMM categorized by Steiner Analysis reference value of ANB

ANB	$<4^o$ & $>0^o$ (I)	$>4^o$ (II)	$<0^o$ (III)
Number of Subjects	15	33	6
Maxillary (mm)	88	95.85	84.63
Mandibular(mm)	83.11	87.41	82.67
RMM	0.945	0.915	0.978

Table 4.13. Influence of Steiner ANB Classification on ratio of Mandibular Radius to Maxillary Radius (RMM)

Tests of Between-Subjects Effects					
Dependent Variable: RMM					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.025	2	.012	2.971	.060
Intercept	30.521	1	30.521	7352.721	.000
Steiner ANB	.025	2	.012	2.971	.060
Error	.212	51	.004		
Total	46.926	54			
Corrected Total	.236	53			

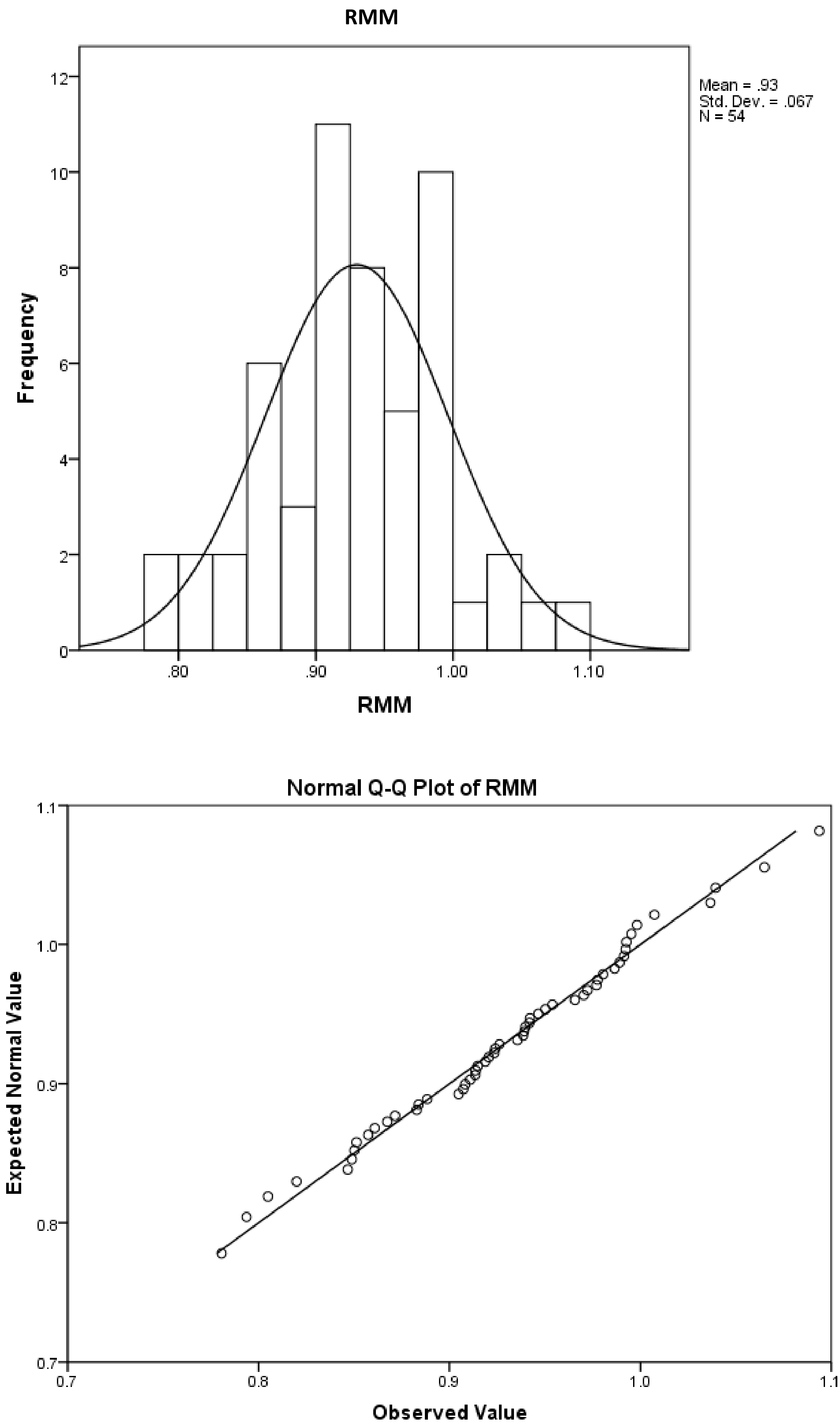


Fig. 4.7. Frequency distribution and Q-Q plot of RMM.

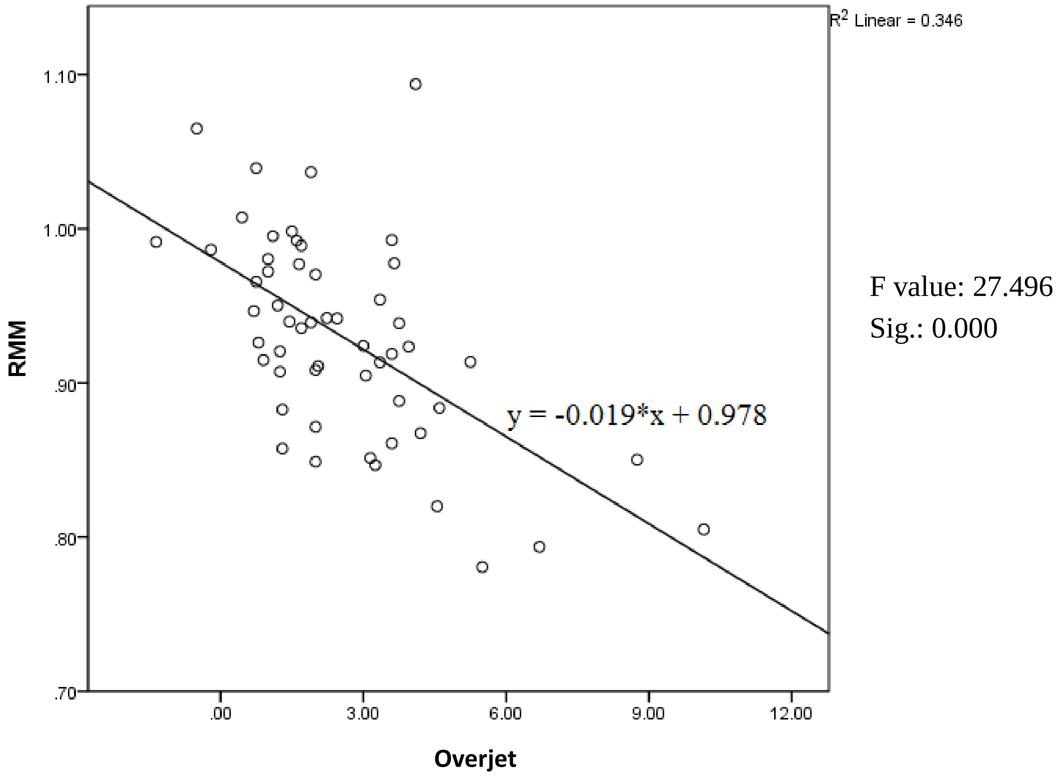


Fig. 4.8. Linear regression of RMM and Overjet.

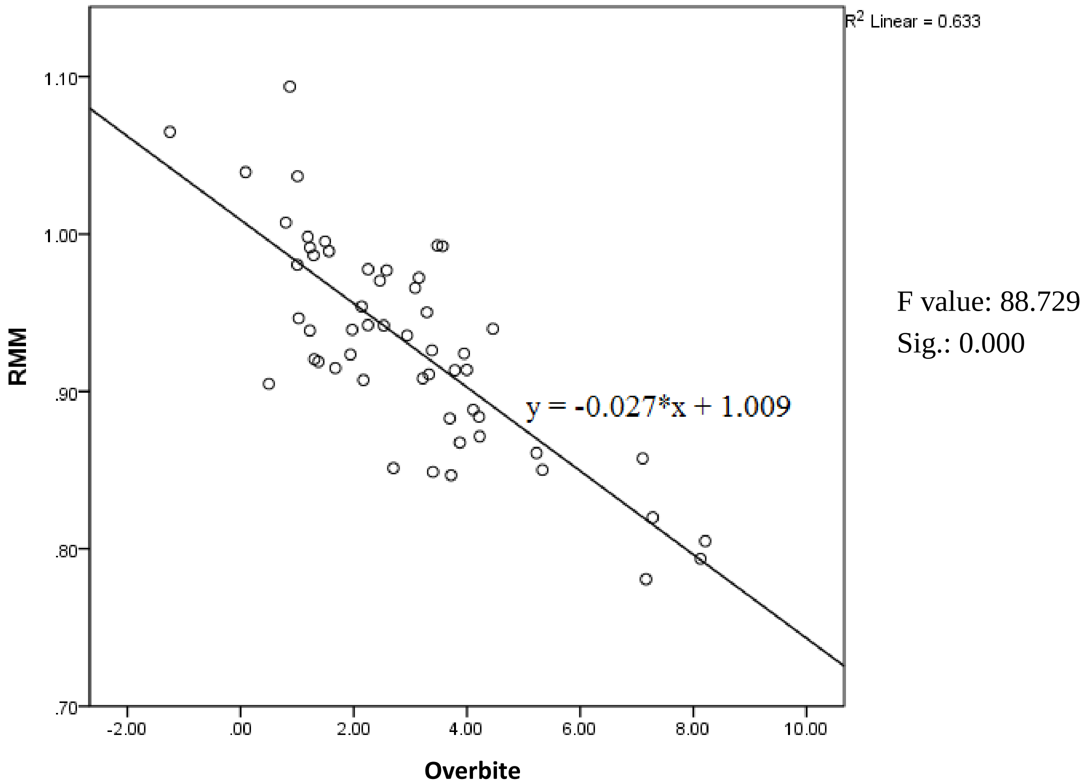


Fig. 4.9. Linear regression of RMM and Overbite.

4.3 Distance between Summits of two Condylar Heads (DisCH)

The distance between the summits of two condylar heads (DisCH) ranges from 92 mm to 112.39 mm (mean: 100.87, Std.: 4.2mm) (Table 4.14). There is a significant difference between the groups categorized by gender or age (Table 4.15), indicating that the males and the adults have a greater width between the summits of condyles than do the females and the teenagers, respectively. Pearson Correlation shows that DisCH correlates only to B-Angle positively and weakly. Normal distribution confirmation is shown in Fig. 4.10.

Table 4.14. Distribution of distance between summits of two condylar heads (DisCH)

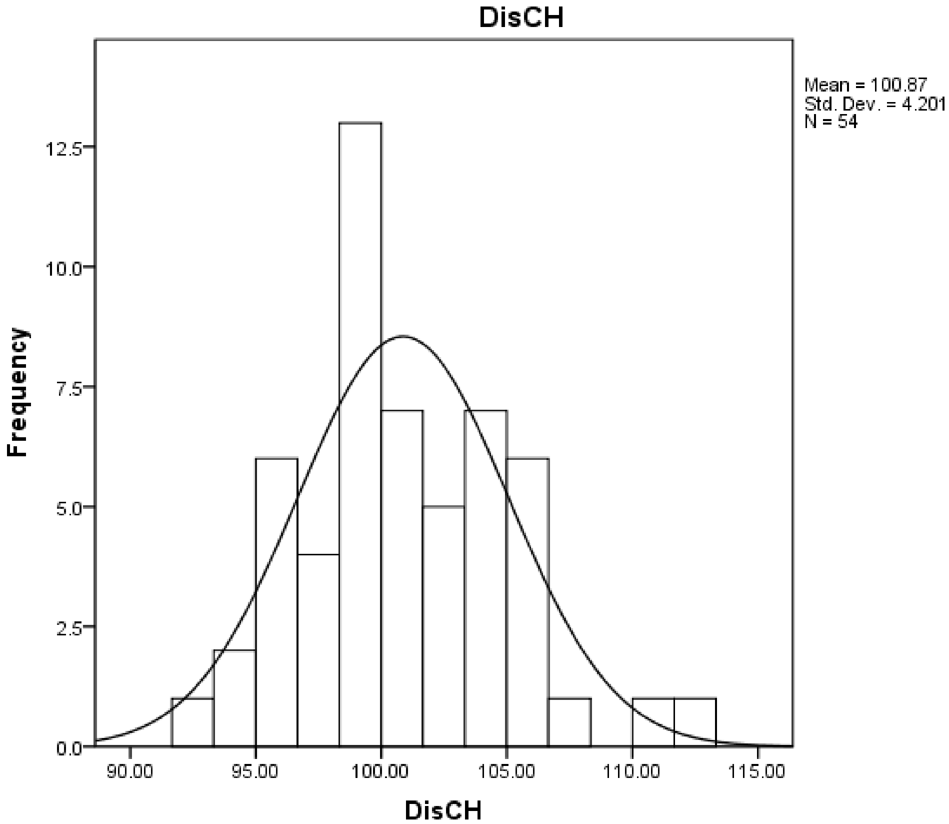
	N	Mean (mm)	Std. (mm)	Minimum	Maximum
Female	43	100.06	3.54	92	106.36
Male	11	104.01	5.23	94.79	112.39
<20 years	40	98.72	2.65	94.79	105.21
>= 20 years	14	101.62	4.4	92	112.39
Total	54	100.87	4.2	92	112.39

Table 4.15. Influence of gender and age on DisCH

Tests of Between-Subjects Effects

Dependent Variable: DisCH

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	285.930	3	95.310	7.338	.000
Intercept	313718.197	1	313718.197	24154.099	.000
Gender	104.862	1	104.862	8.074	.006
Age	149.077	1	149.077	11.478	.001
Gender * Age	31.799	1	31.799	2.448	.124
Error	649.410	50	12.988		
Total	550360.108	54			
Corrected Total	935.340	53			



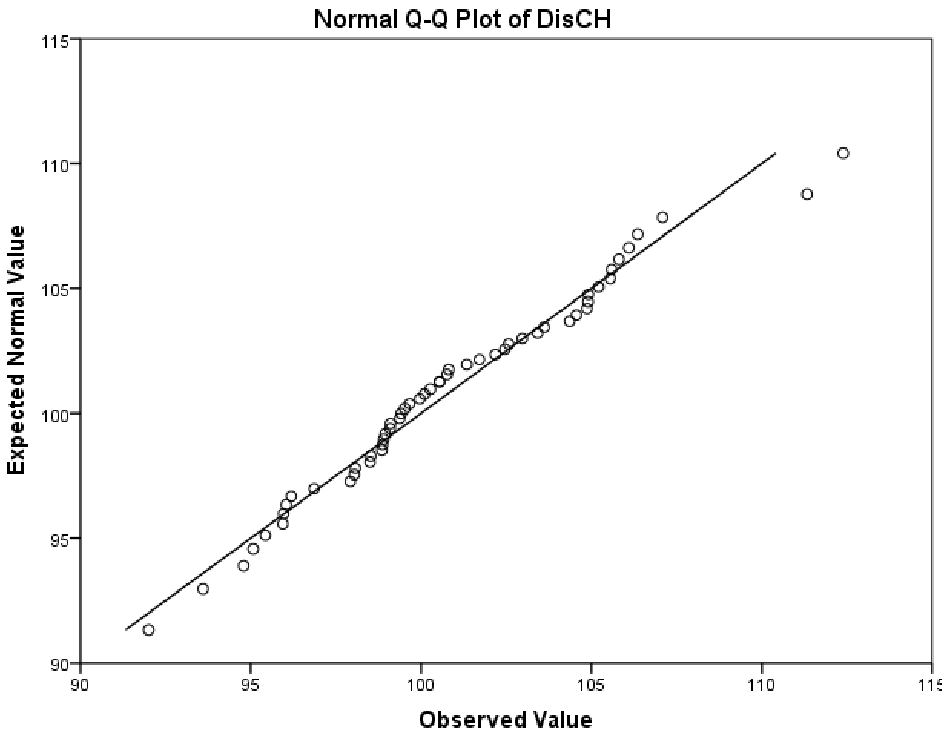


Fig. 4.10. Frequency distribution and Q-Q plot of DisCH.

4.4 Angulation of Mediolateral Axes of Two TMJs (M-Angle)

The distribution of M-Angle in frequencies is shown in Fig. 4.11, followed by the scatter plots concerning the two roughly moderately correlated variables: Condylar Height and Overjet (Figs. 4.12 and 4.13, respectively). Meanwhile, the data in Fig. 4.13 are grouped by the Steiner ANB classification, resulting in a significant effect on M-Angle (Table 4.16). The linear regression model of M-Angle and Overjet is also significant (Table 4.17).

Table 4.16. Effect of Steiner ANB Classification on M-Angle

Tests of Between-Subjects Effects

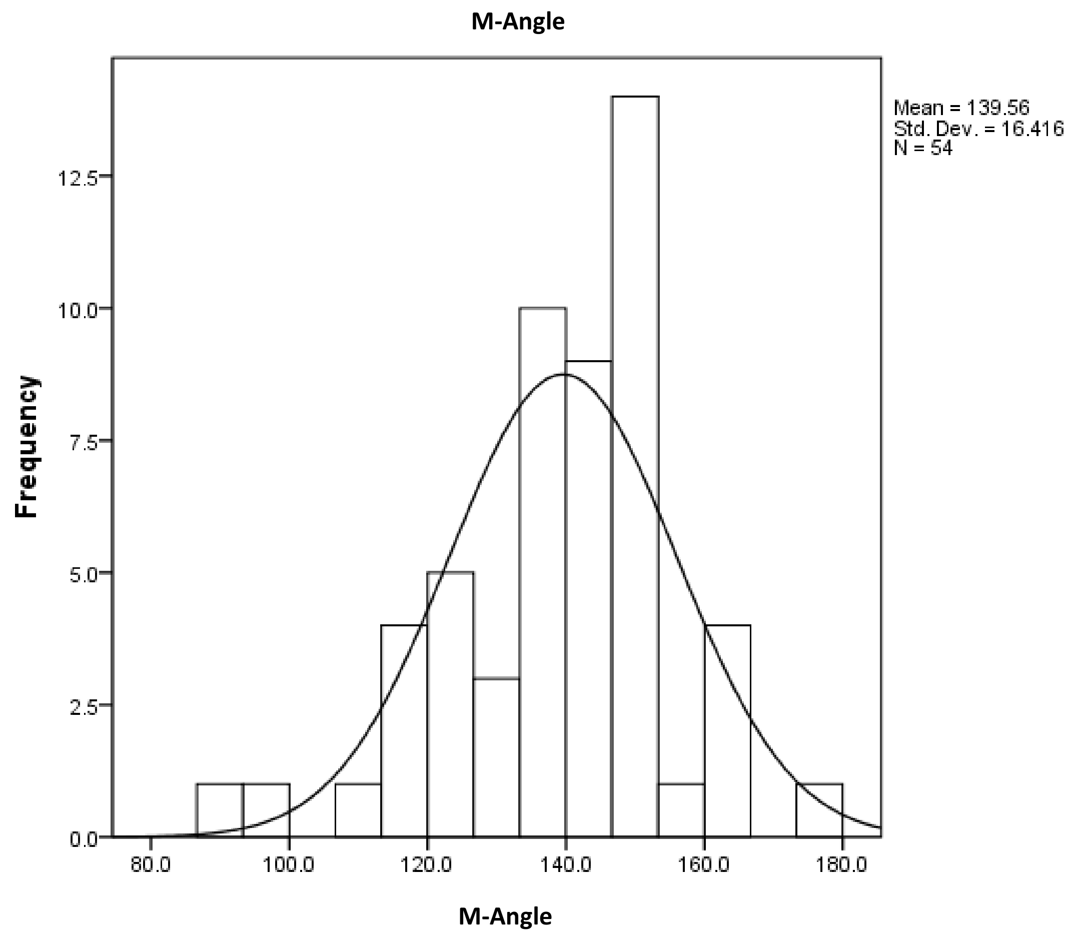
Dependent Variable: M-Angle

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1844.503	2	922.252	3.782	.029
Intercept	698801.537	1	698801.537	2865.396	.000
Steiner ANB	1844.503	2	922.252	3.782	.029
Error	12437.682	51	243.876		
Total	1066090.081	54			
Corrected Total	14282.185	53			

Table 4.17. Linear regression model of M-Angle to Overjet

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3130.148	1	3130.148	14.595	.000
	Residual	11152.037	52	214.462		
	Total	14282.185	53			



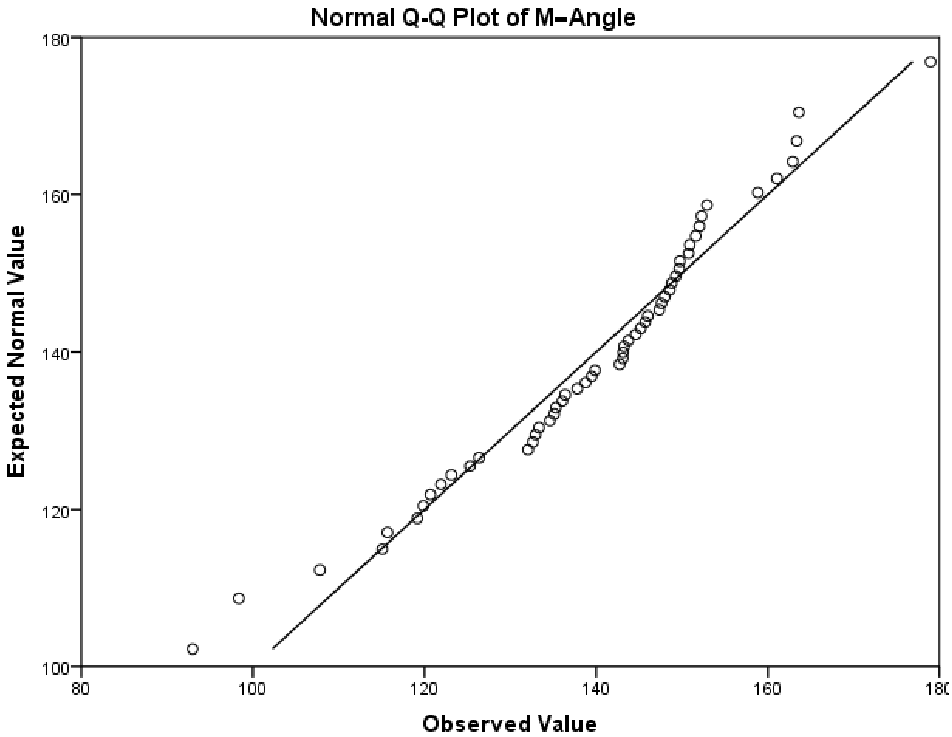
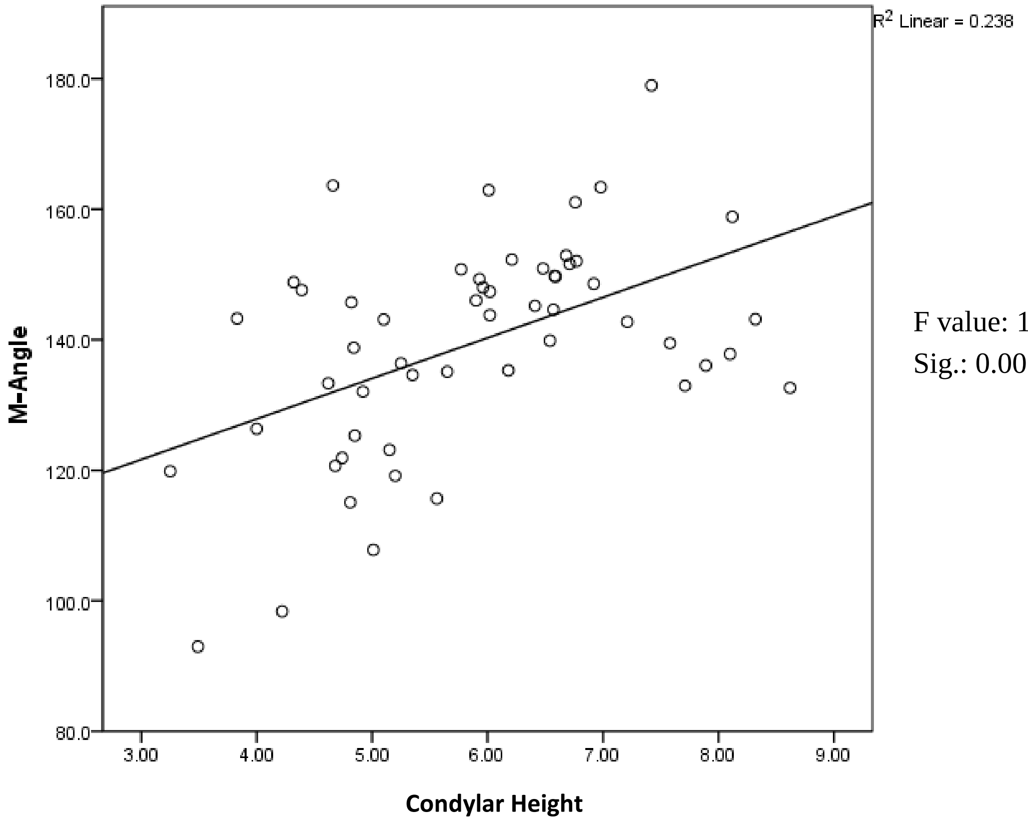
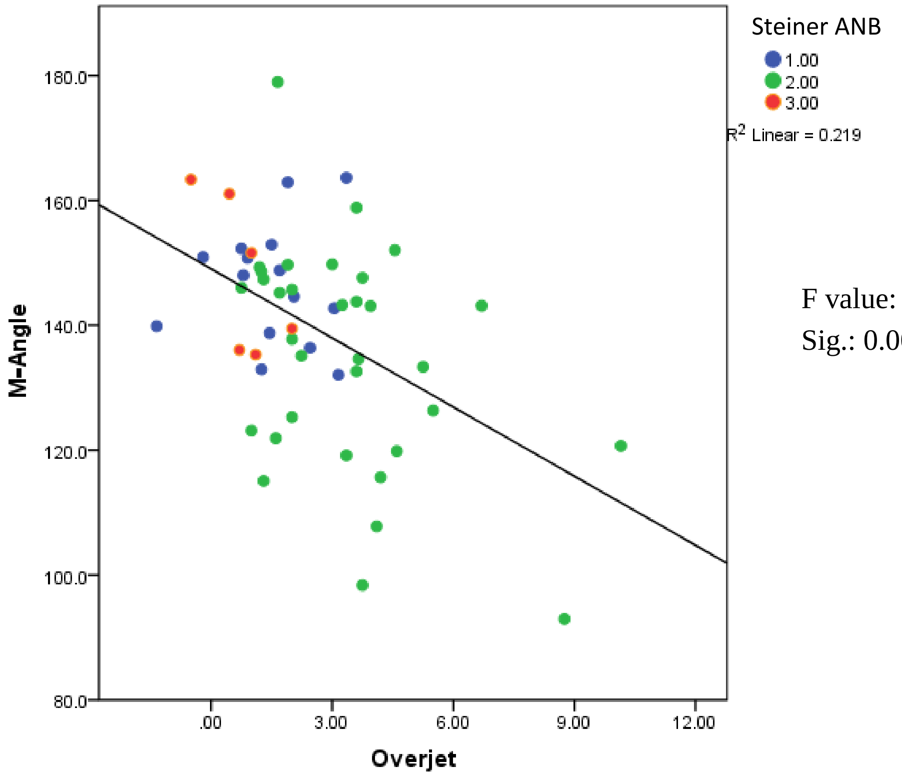


Fig. 4.11. Frequency distribution and Q-Q plot of M-Angle.



F value: 16.21
Sig.: 0.000

Fig. 4.12. Scatter plot of M-Angle to Condylar Height.



F value: 14.595
Sig.: 0.000

Fig. 4.13. Relationship between M-Angle and Overjet, subjects grouped by Steiner ANB at meantime.

4.5 Bonwill's Angle (B-Angle)

As shown in the histogram of frequencies (Fig. 4.14), the number of subjects with low value is slightly greater than that of those with high value. Overbite, DisCH and Condylar Height have a linear relationship with B-Angle (respectively Figs. 4.15, 4.16 and 4.17), and Pearson Correlation shows the former two to be weakly positive while the latter one is weakly negative (Table 4.9).

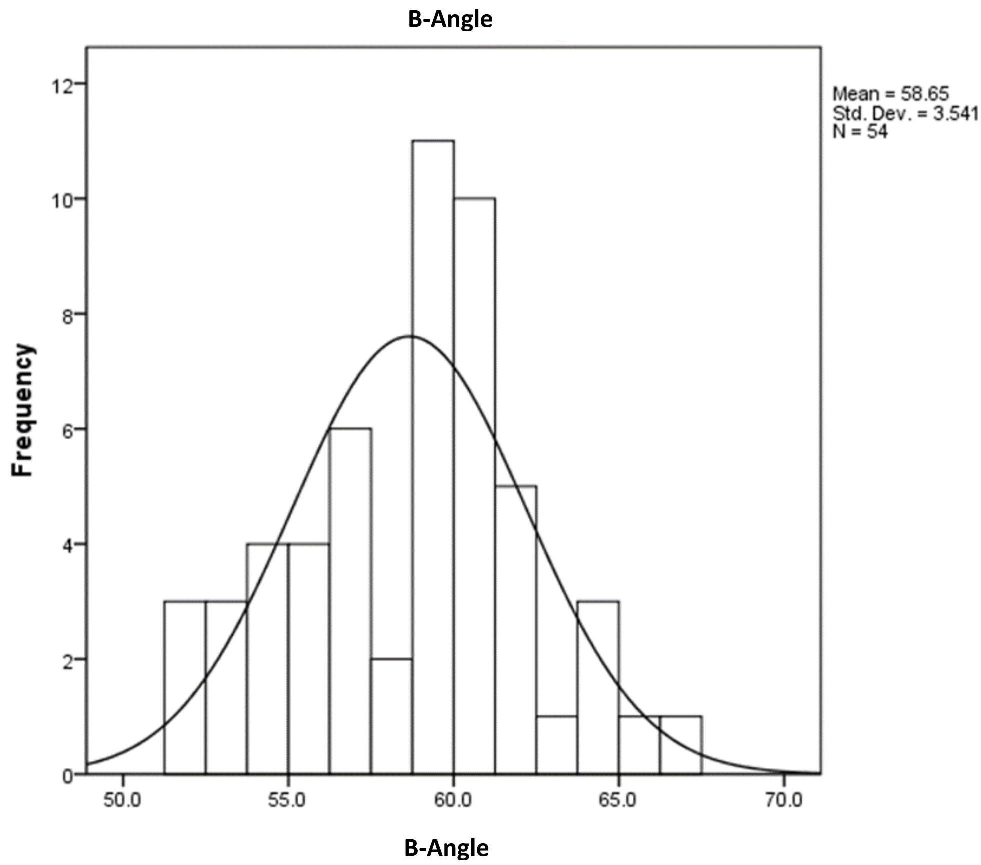


Fig. 4.14. Frequency distribution and Q-Q plot of B-Angle. (continued)

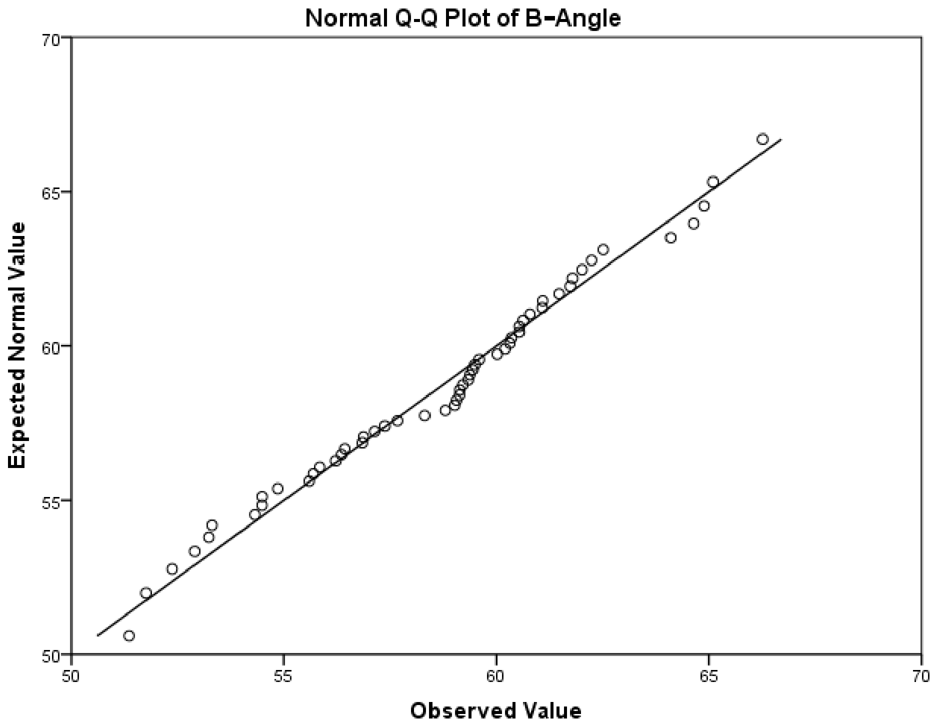
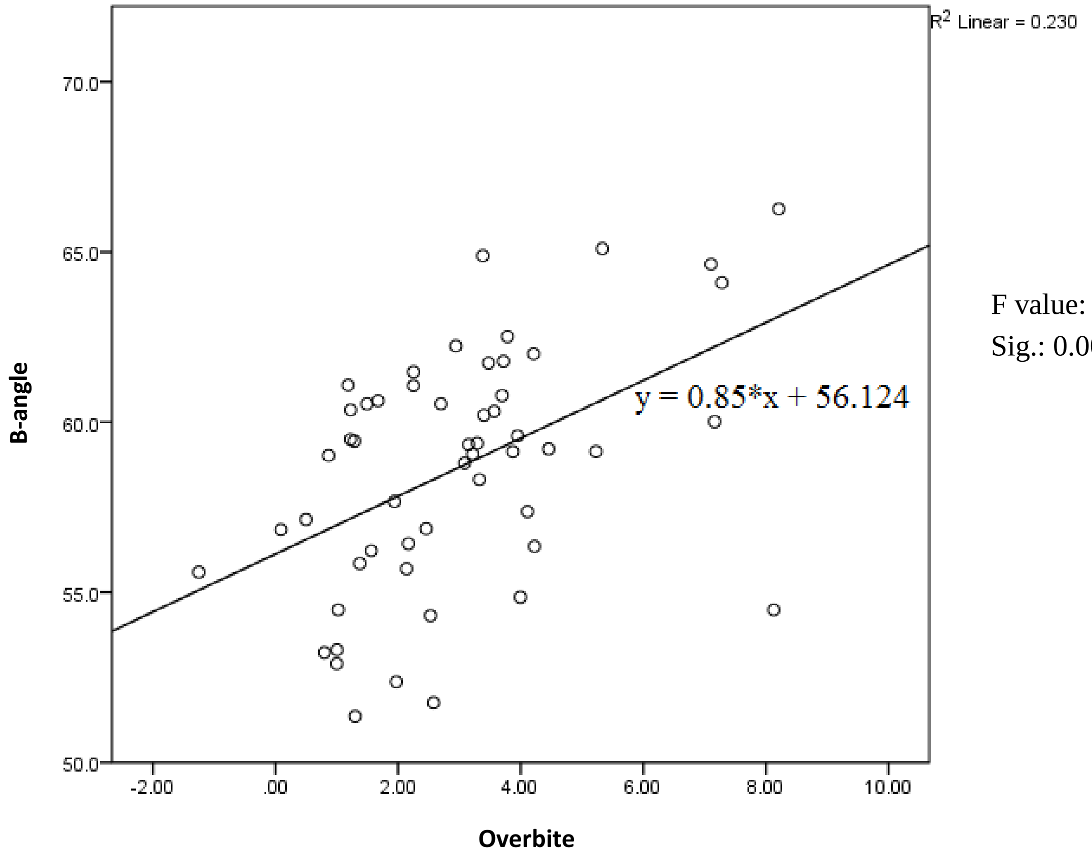


Fig. 4.14. Frequency distribution and Q-Q plot of B-Angle.



F value: 15.562
Sig.: 0.000

Fig. 4.15. Relationship between B-Angle and Overbite.

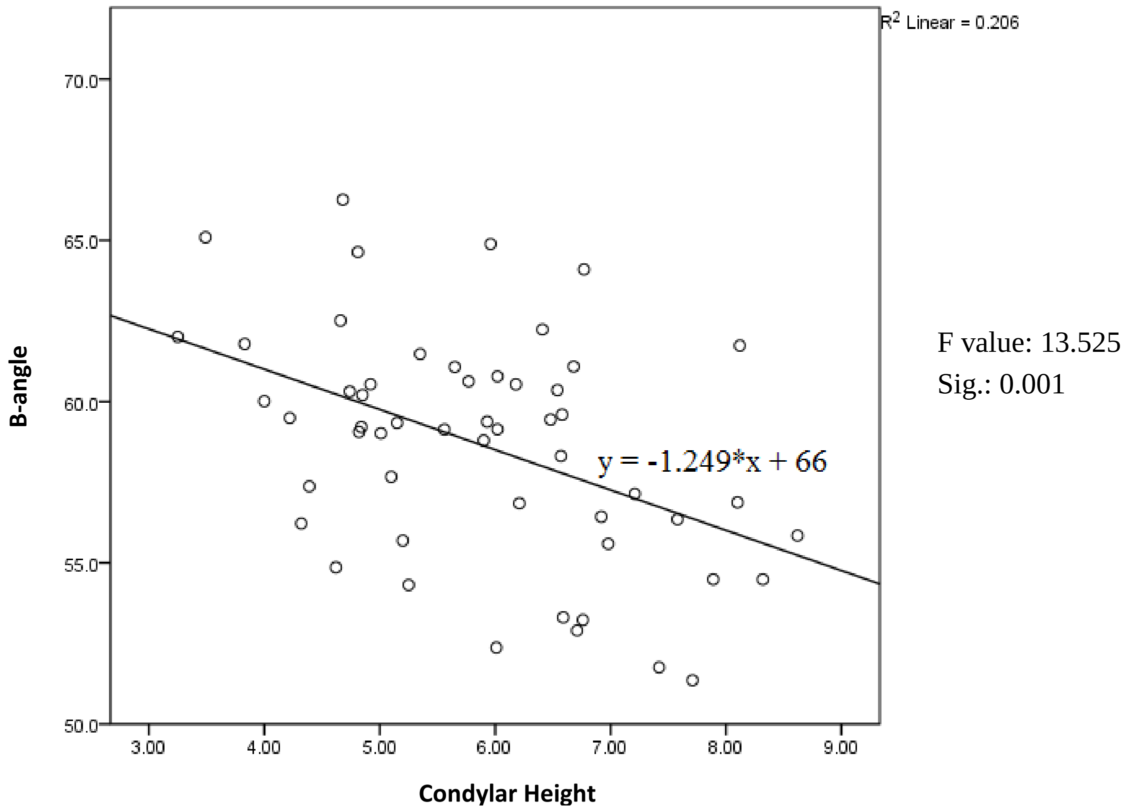


Fig. 4.16. Relationship between B-Angle and Condylar Height.

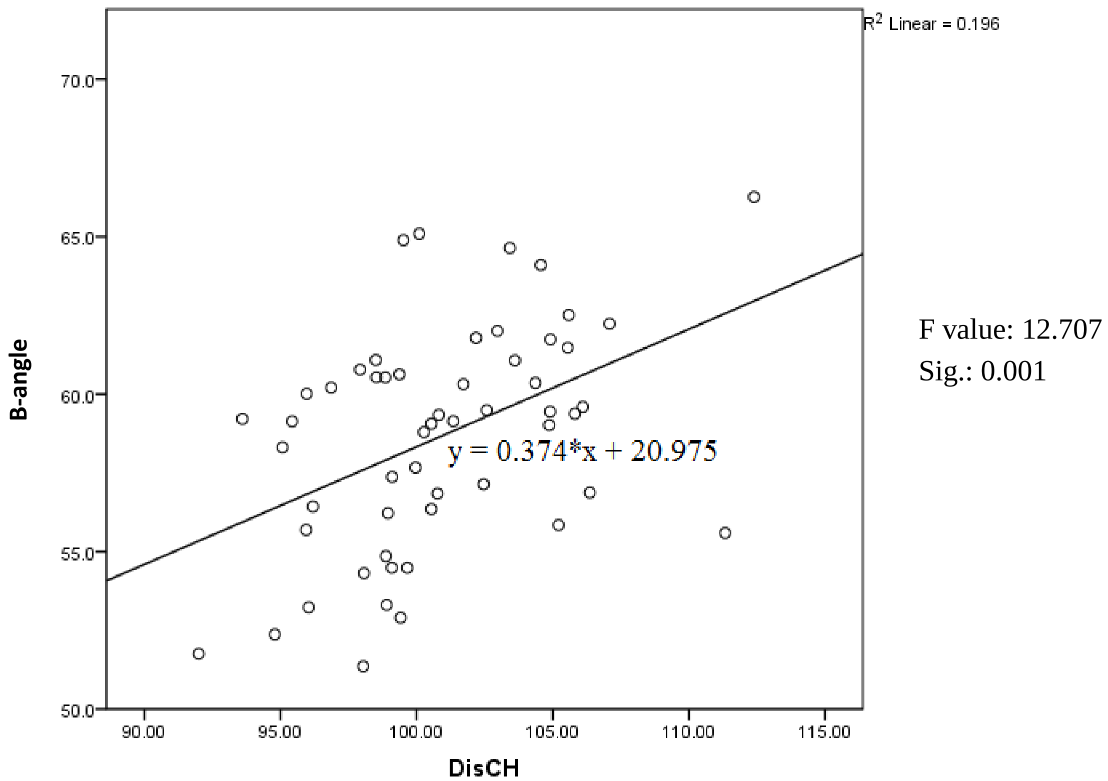


Fig. 4.17. Relationship between B-Angle and DisCH.

4.6 ANB

Further to its moderate correlation to Maxillary Radius, ANB also is moderately correlated to Overjet and weakly to Overbite in a positive way, whereas a weak negative correlation exists between Condylar Height and ANB. Figs. 4.18, 4.19 and 4.20 show the linear regression results of ANB to Overjet, Overbite and Condylar Height; additionally, ANB is close to the normal distribution (Fig. 4.21).

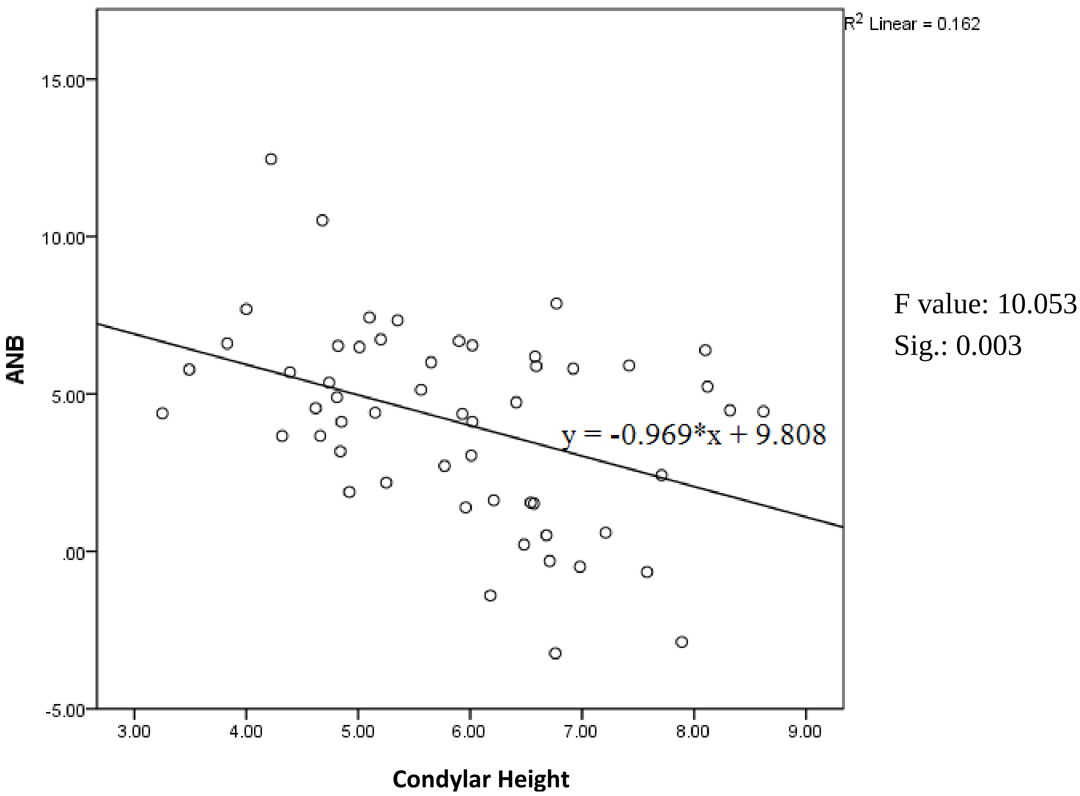
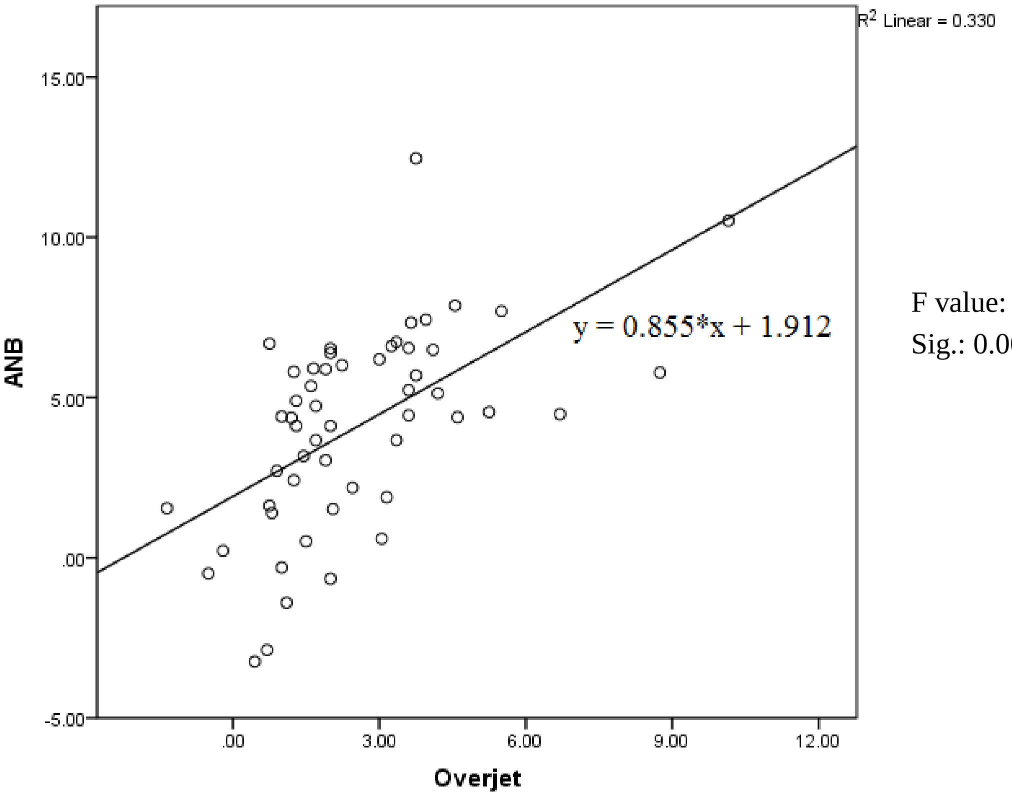
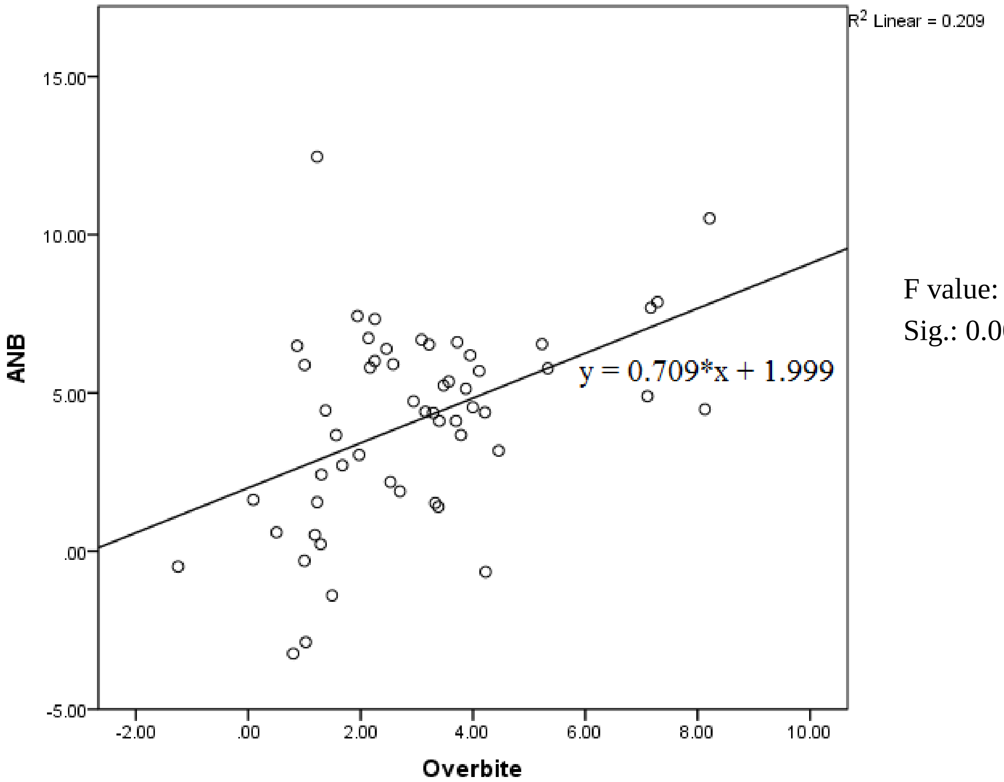


Fig. 4.18. Relationship between ANB and Condylar Height.



F value: 25.647
Sig.: 0.000

Fig. 4.19. Relationship between ANB and Overjet.



F value: 13.756
Sig.: 0.001

Fig. 4.20. Relationship between ANB and Overbite.

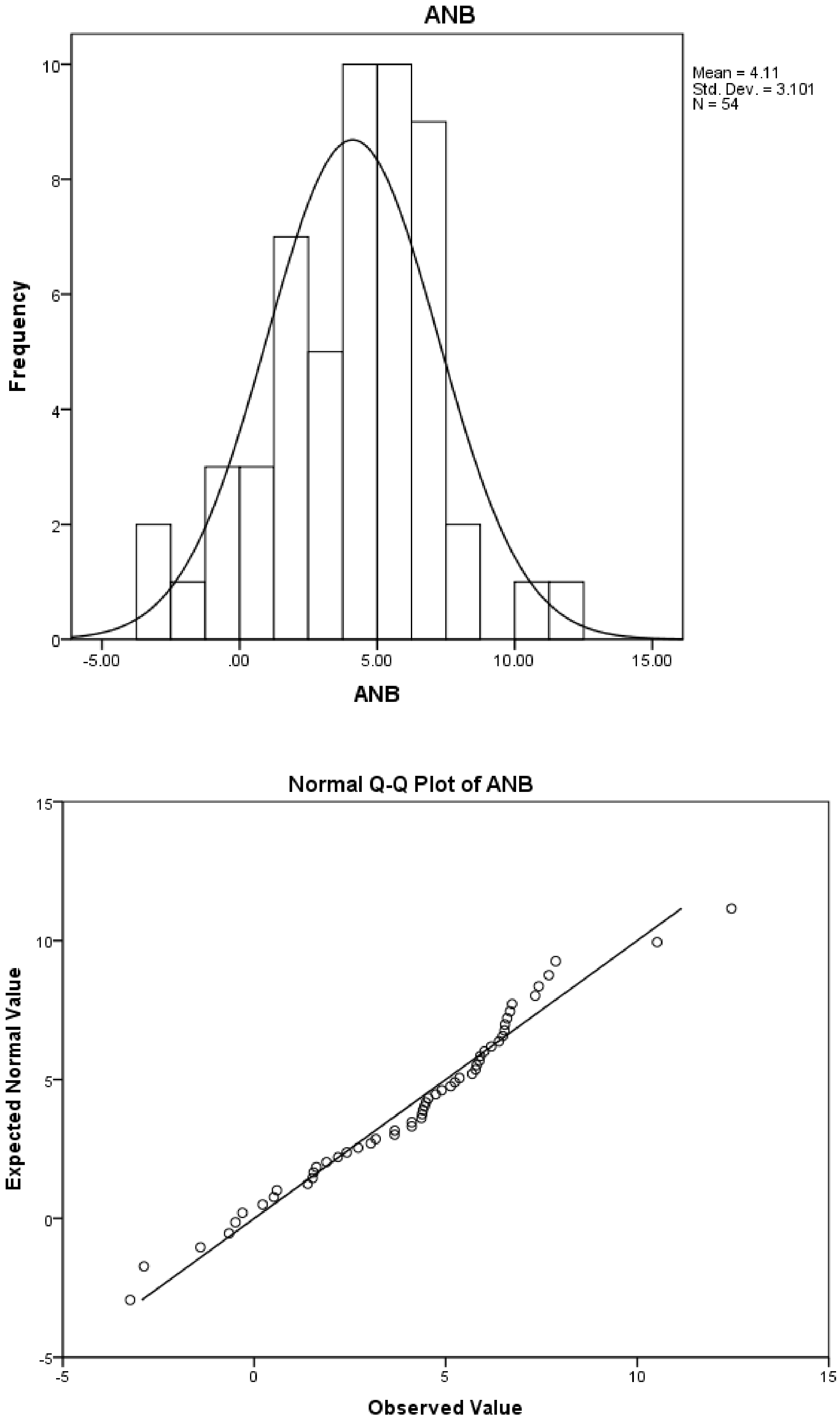
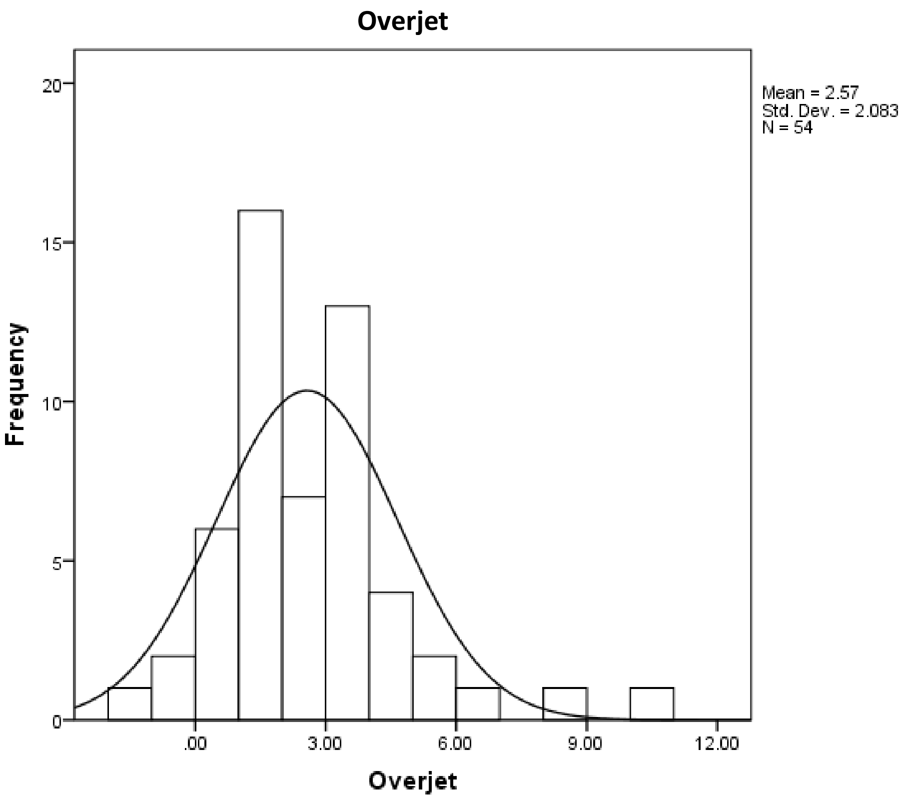


Fig. 4.21. Frequency distribution and Q-Q plot of ANB.

4.7 Overjet and Overbite

Figs. 4.22 and 4.23 illustrate that the distribution of Overjet and Overbite are not normalized ideally, especially in the left tail of the population. This phenomenon indicates that the subjects did not generate greater negative values of Overjet and Overbite; however, patients generating such values usually possess the severe Skeletal Class III or open bite characteristics, and they do not commonly present in general clinical routines. Therefore, the distribution could be reasonable and not attributed to subjective error of the investigator. Moreover, Overjet and Overbite exhibit a positive linear relationship (Fig. 4.24), and the values of Pearson Correlation, involving those three variables (RMM, Overjet and Overbite) are almost the top three, so it might be inferred that those three variables could be linearly correlated in a three-dimensional space.



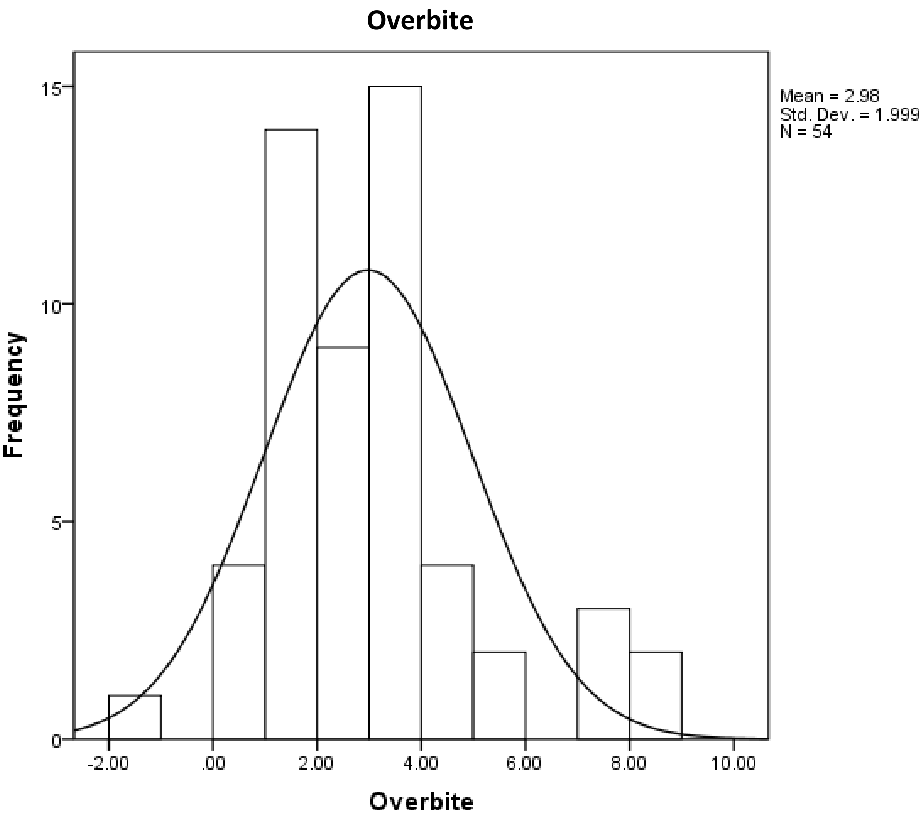


Fig. 4.22. Frequency distribution of Overjet and Overbite.

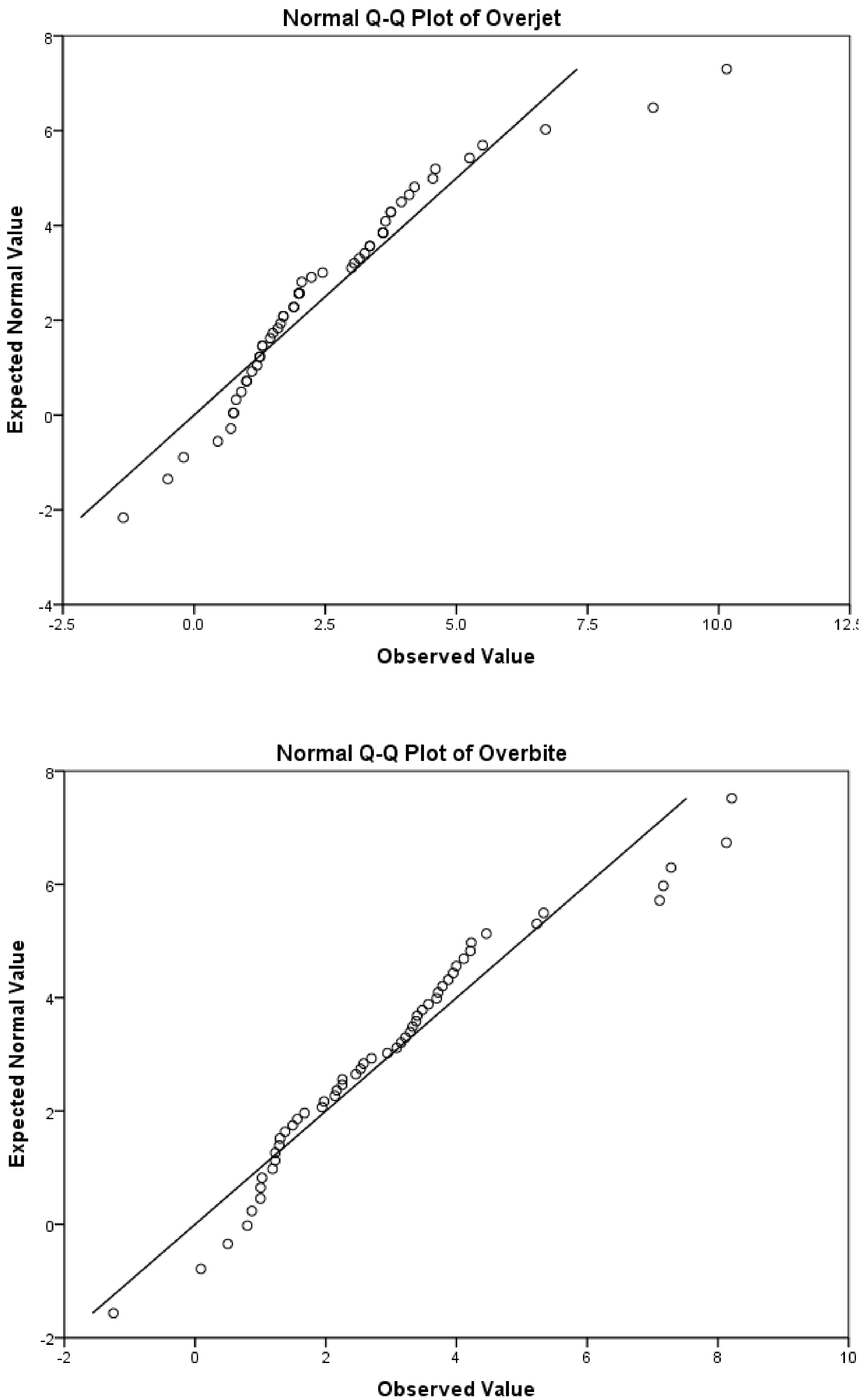
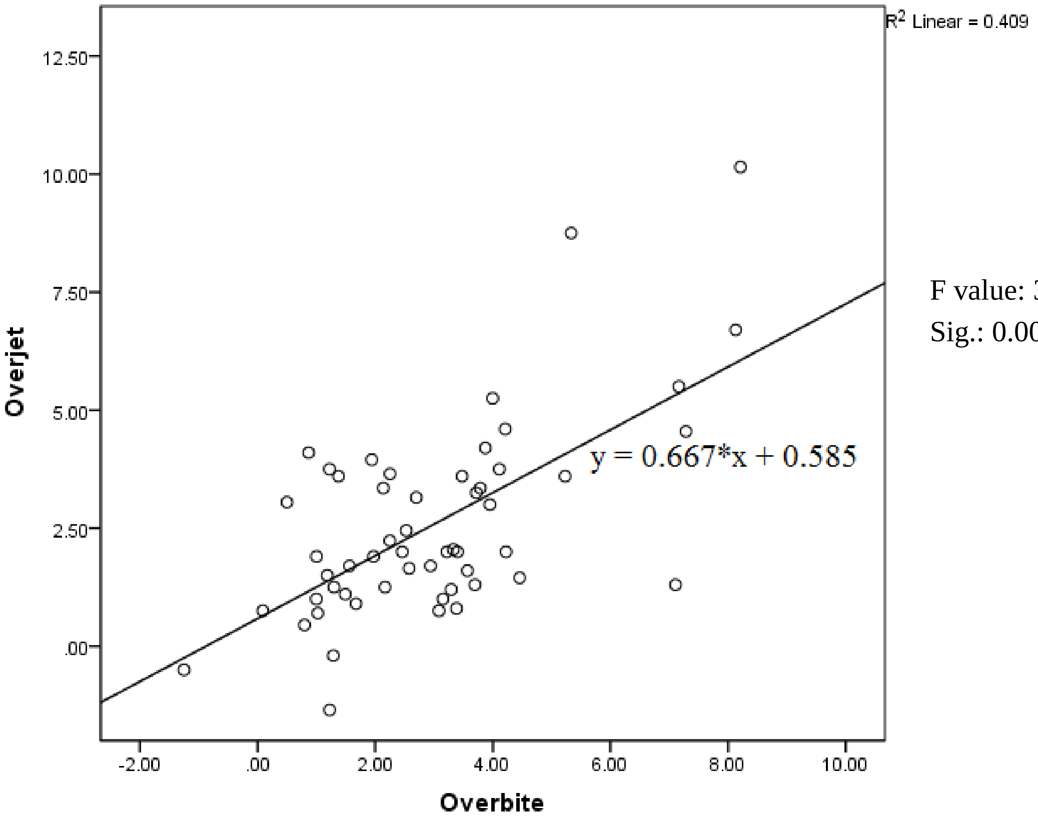


Fig. 4.23. Q-Q plots of Overjet and Overbite.

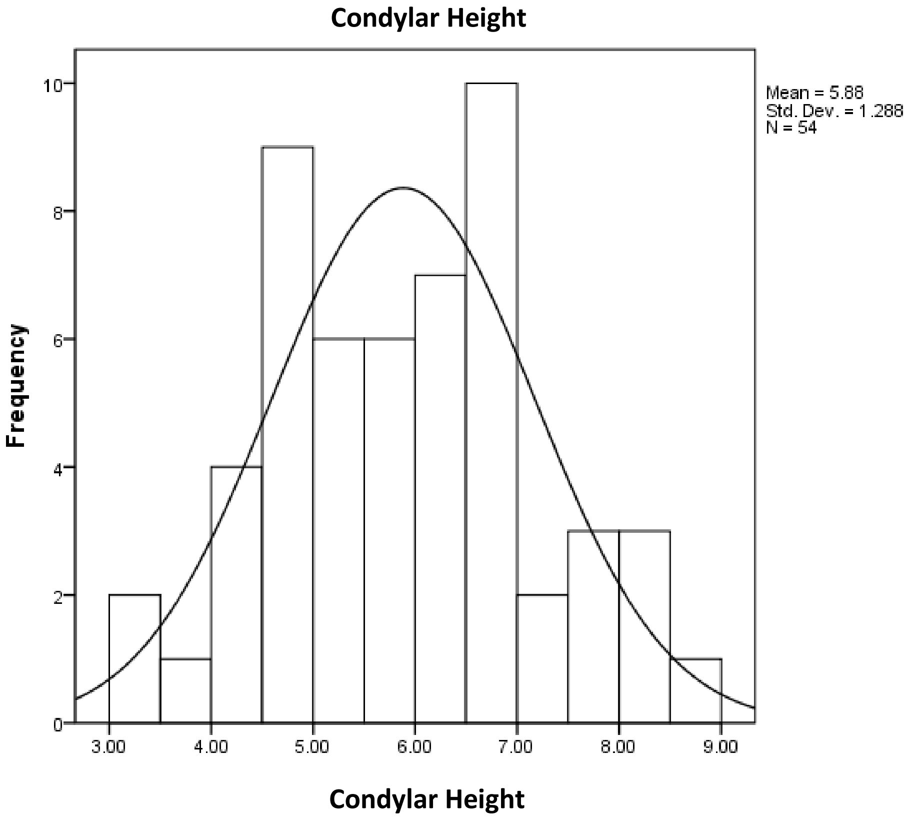


F value: 36.035
Sig.: 0.000

Fig. 4.24. Relationship between Overjet and Overbite.

4.8 Condylar Height

According to the frequency histogram and Q-Q plot of Condylar Height (Fig. 4.25), the values of Condylar Height seem to approximate the normal distribution. Linear regression was performed using several methods (stepwise, backward and forward) to determine the variables influencing Condylar Height. It is noted that RMM is generated by the radii of the two Monson's Spheres and that RMM represents the magnitude of discrepancy of the two radii, so the independent variables included all the variables except the two Monson's Sphere radii while the dependent variable was Condylar Height. Table 4.18 shows that the independent variables (i.e., M-Angle, B-Angle and DisCH) are significant on Condylar Height, while ANB does not have significant influence on Condylar Height. In addition, a weak negative correlation appears to exist between Condylar Height and Maxillary Radius (Table 4.9).



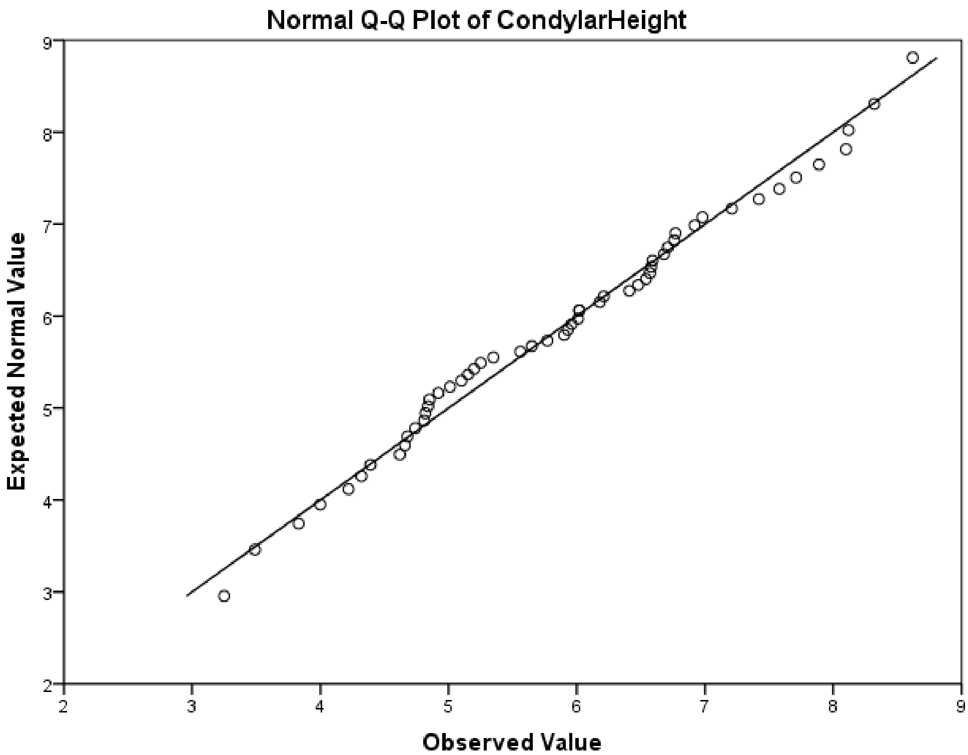


Fig. 4.25. Frequency distribution and Q-Q Plot of Condylar Height.

Table 4.18. Linear regression of Condylar Height as dependent variable

Coefficients						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.432	3.933		.618	.539
	M-Angle	.022	.009	.280	2.320	.025
	B-Angle	-.153	.047	-.422	-3.256	.002
	ANB	-.093	.050	-.224	-1.877	.066
	DisCH	.097	.037	.316	2.614	.012

Based on the pair-wise linear relationships among RMM, Overjet and Overbite (Figs. 4.8, 4.9 and 4.24), a 3D scatter diagram (Fig. 4.26), generated at www.plot.ly, exhibits that these three variables appear to spread across the space roughly linearly, where both Overjet and Overbite decrease with the rise of RMM. Furthermore, the 54 subjects were divided into three groups in terms of their Condylar Heights in a particular ascending order (Table 4.19). MANOVA, containing the three variables as a dependent unit and the levels of Condylar Height as a fixed factor (Condylar HeightFX), was used to confirm that the three groups were significantly different (Sig. Value: 0.04, Table 4.20), as shown in Fig. 4.26. In summary, with the shift of the Condylar Height level in an ascending order (black-pink-green, Fig. 4.26), there appears to be a trend wherein both Overjet and Overbite are negatively related to this shift and the association of this shift to RMM is positive, which suggests that all four variables are likely relevant to one another. Therefore, instead of a research focus on one specific variable for TMJs, a group of variables may need to be considered together for TMJ issues.

Table 4.19. Distribution of Condylar Height after trisection

Condylar Height as fixed factors	Mean (mm)	N	Std. (mm)
Black: low-value level group	4.5	18	0.5
Pink: moderate-value level group	5.9	18	0.4
Green: high-value level group	7.3	18	0.7
Total	5.9	54	1.3

Note: The 54 subjects were trisected into 3 groups (18 subjects per group) in accordance with the values of Condylar Height in an ascending order.

Table 4.20. Multivariate linear model with Overjet, Overbite and RMM as dependent variables

Multivariate Tests						
Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.998	10775.221	3	49	.000
	Wilks' Lambda	.002	10775.221	3	49	.000
	Hotelling's Trace	659.707	10775.221	3	49	.000
	Roy's Largest Root	659.707	10775.221	3	49	.000
Condylar HeightFX*	Pillai's Trace	.230	2.167	6	100	.052
	Wilks' Lambda	.774	2.238	6	98	.046
	Hotelling's Trace	.288	2.305	6	96	.040
	Roy's Largest Root	.271	4.513	6	50	.007

* Condylar HeightFX: three levels of Condylar Height.

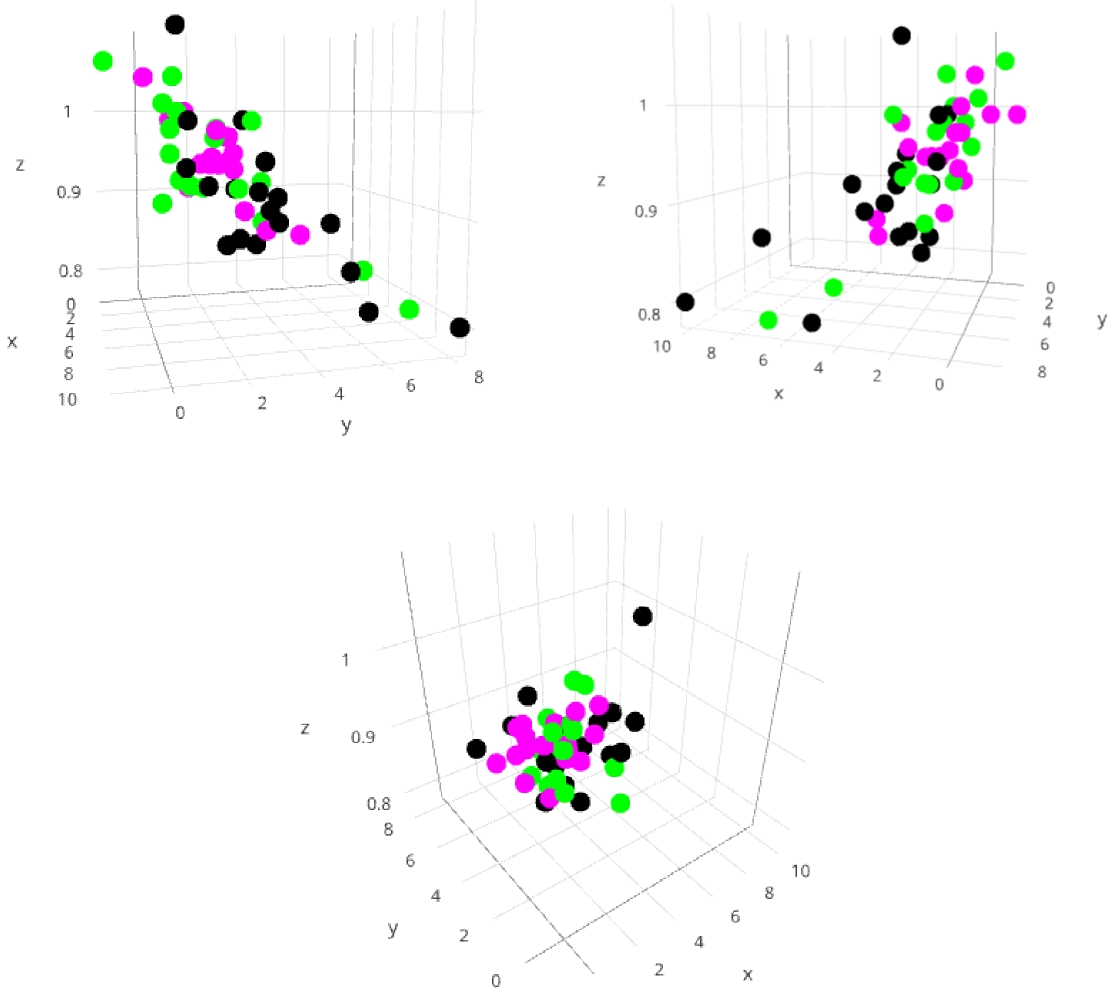


Fig. 4.26. Exhibition of correlation of dentofacial characteristics and Condylar Height. x: Overjet; y: Overbite; z: RMM. (generated at www.plot.ly).

CHAPTER 5 DISCUSSION

5.1 Monson's Sphere

The general average mandibular radius in the Chinese ethnic group population is 85.69 mm, which is less than those of other ethnic groups, e.g., 101 mm in Caucasian young adults (Ferrario *et al*., 1999); 110.6 mm in Japanese young adults (Kagaya *et al*., 2009); 110.89 mm in Korean young adults (Nam *et al*., 2013). Only 3 cases out of the 54 subjects studied measured near to100 mm. The maxillary radii were found to be greater than the mandibular ones, which agrees with the findings from a study on Japanese adults (Xu, Suzuki, Muronoi & Ooya, 2004). Further, and as suggested by Xu, Suzuki, Muronoi and Ooya (2004) and Ferrario *et al*. (1999), the mandibular radii of the subjects indicated no gender difference. Although in Kagaya *et al*., 2009, Fueki, Yoshida & Igarashi, 2013 and Nam *et al*., 2013, the authors found that compared to the female subjects the male subjects obtained a larger radius of the sphere upon the mandibular teeth, in the present study significant gender difference exists only in the maxillary radius.

Several reasons may contribute to the divergence in results between the present study and those in the literature. First, in comparison with the subjects in this thesis, the subjects recruited in most of the others' studies (Ferrario *et al*., 1999; Xu, Suzuki, Muronoi & Ooya, 2004; Fueki, Yoshida & Igarashi, 2013; Nam *et al*., 2013) were of a much narrower age range, and as well, Angle's Class I occlusion was a required condition in some of those studies (Ferrario *et al*., 1999; Xu, Suzuki, Muronoi & Ooya 2004; Kagaya *et al*., 2009; Fueki, Yoshida & Igarashi, 2013). Second, some of the calculations in the literature excluded the incisors (Xu, Suzuki, Muronoi & Ooya, 2004; Fueki, Yoshida & Igarashi, 2013; Nam *et al*., 2013), while others included all the teeth for the measurement (Ferrario *et al*., 1999; Kagaya *et al*., 2009). Meanwhile, the TMJ information was rarely exploited except for by Kagaya *et al.* (2009), who used the mid-point of the two condylar heads of the articulator. Finally, Monson's Sphere, as a combination of the curves of Wilson and Spee in the transversal and sagittal planes, respectively, could differ due to different ways of measuring the two curves. Therefore, possible different and even controversial conclusions may result.

Fig. 4.1 demonstrates that the two radii were roughly in normal distribution, and that the distribution of RMM appears to be a little bit more normalized (Fig. 4. 7). Although there was no significant difference in Mandibular Radius classified by the Steiner ANB classification (Table 4.10), Mandibular Radius coupled with Maxillary Radius was impacted by the Steiner ANB classification (Table 4.8). The correlation between the maxillary and mandibular arches, which can be represented by the ratio of mandibular radius to maxillary radius (RMM), shows the deviation, but this is not significant based on the skeletal relationships (grouped by the Steiner ANB classification) (Table 4.13). RMM, as the inter-arch indicator, means the lower the RMM, the greater the inter-arch deviation, and the more squeezed or deeper the mandibular radii compared to the relative maxillary ones. RMM rises with respect to the skeletal relationship in the order of: Class II, Class I and Class III (Table 4.12), which is crudely in common with the conclusion of Veli, Ozturk and Uysal (2015) that the depth of the Curve of Spee increased with the order of Angle Classification Class II, Class I and Class III. Since RMM has a negative linear correlation with Overjet and Overbite (Figs. 4. 8 and 4. 9), it can be inferred that Overjet and Overbite increase while RMM decreases; in other words, a subject with a more squeezed mandibular sphere, compared to the maxillary one, tends to obtain larger Overjet and Overbite. This result is similar to those suggested by Baydaş *et al*. (2004) and

Cheon *et al*. (2008).

5.2 General Profile of Variables affecting Condylar Height

In many studies, Overjet was suggested to be a risk factor for TMDs (Nordström & Hansson, 1986; Pullinger, Seligman & Gornbein, 1993; Kanh *et al.*, 1998; Pullinger & Seligman, 2000; Celić, Jerolimov & Pandurić, 2002). Overbite was also connected to morphologic changes of condylar heads (Solberg, Bibb, Nordström & Hansson, 1986). Hiiemäe (1967) observed that "Since the masticatory apparatus functions as an integrated unit, it follows that the structure of any of its parts can only be explained in terms of its function and that with reference to the mechanism of function of the system as a whole.'' Further, many researchers highlighted the caution of using only the occlusal features to identify TMDs (Kahn *et al.*, 1999; Pullinger & Seligman, 2000; Celić, Jerolimov & Pandurić, 2002), so any analysis regarding the shape of the condylar head ought as much as possible to include the potential dentofacial characteristics.

The Pearson Correlation matrix (Table 4.9) presents the fundamental correlation of Condylar Height to other variables. The spectrum of the significant variables can be depicted when Condylar Height is at a low value range, or a risky level, because B-Angle, ANB, Overjet and Overbite are rising while Condylar Height is falling, (except the shift of RMM [close to a significant level] and M-Angle are in an opposite way.) Linear regression and MANOVA also confirmed this relationship (Tables 4.18 and 4.20 and Fig. 4.26). Although DisCH has no significant bivariate correlation with Condylar Height, it is influential as one of the multiple independent variables in the linear regression (Table 4.18), and might be considered to be the physiological component of the multifactorial influence in the analysis. B-Angle is an extension of the concept Bonwill's Triangle in which the value of B-Angle is proposed to be 60º. The mean value of B-Angle in the low-level Condylar Height group is the greatest amongst all three groups and is more than 60º (Table 5.1), where differences among these groups are significant (Table 5.2). This could be a coincidence due to the small sample size; however, the feature of condyle-incisor contour, as the general shape of the functional interface of the mandible, may interact with the shape of condyle heads; that is, an obtuse triangle tends to be accompanied by low-height condyles.

Table 5.1 Mean value of B-Angle of subjects grouped by Condylar HeightFX

	B-Angle		
Condylar HeightFX	Mean	N	Std.
1*	60.3	18	3.013
2*	59.2	18	2.936
3*	56.4	18	3.527
Total	58.7	54	3.541

* level 1: low condylar height group; level 2: medium value group; level 3: high value group.

Table 5.2 Difference of B-Angle among subjects grouped by Condylar HeightFX

Tests of Between-Subjects Effects

Dependent Variable: B-Angle

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	152.260	2	76.130	7.579	.001
Intercept	185772.536	1	185772.536	18493.330	.000
Condylar HeightFX	152.260	2	76.130	7.579	.001
Error	512.314	51	10.045		
Total	186437.111	54			
Corrected Total	664.575	53			

To summarize, in clinical description, the patients with lower-value condylar height are likely to have a profile comprising larger ANB, Overjet, Overbite, closer distance from the mandibular incisors to condyles (greater B-Angle) and high discrepancy between the dentition patterns (smaller RMM), so the high-risk group is more likely to be classified into Angle Class II Division 1 along with the skeletal Class II.

It must be stressed that this view does NOT mean to negate the risk in other populations, but rather to describe the most relevant group in the general public. In autopsy studies of young adults, Solberg, Bibb, Nordström and Hansson (1986) concluded that "when combined with age, Angle Class II and III dentitions were associated with temporal and condylar deviation in form (DIF) (P less than 0.05), and more Class II dentitions were accompanied by histologic evidence of remodeling changes in the TMJs." Additionally, subjects of Class II Division 2 in line with most of the above criteria but with a small Overjet, may exhibit low-level Condylar Height as well. According to Katsavrias (2006), flattened condylar heads accounted for 5.25% in the 94 condyles studied from the Class II Division 2 malocclusion subjects. Further, although Katsavrias and Halazonetis (2005) suggested that the shape of condylar heads was longer in the sagittal plane in the Class III group than it was in the two Class II groups, Krisjane et al. (2012) found that articular surface flattening was the most prevalent feature in both skeletal Class II and Class III, but that the Class III patients were under a severe condition (mean ANB: -4.4^{o}) that was far deviated from the counterparts in the present study. Finally, these discrepancies may also be explained by the variables neglected in this thesis, including posterior crossbite and guidance pattern to name just two.

5.3 M-Angle

M-Angle is rarely discussed in the literature and is not often examined in regular clinical practice; nevertheless, M-Angle may well be an essential aspect of condyles regarding the dynamic motions of the mandible.

Ettinger and Feldman (2009) proposed that carnivores possess transversally oriented TMJ fossae, which are tightly fit by the condylar heads, and that this relationship between fossae and condyles "permits a hinge movement of the mandible with little lateral displacement, essential for achieving the crushing motion." Herring (2003) stated that while some carnivores can only rotate around a transverse axis to open their jaws, in contrast some herbivores are restricted in opening by the concave shape of TMJ condyles and instead obtain a greater range of movement in the transverse plane. Fig 5.1 shows that the M-angle of a carnivore is likely to reach 180º, and that these condyles resemble the hinged joint of a door. According to Jenkins (2005), a hinge joint is uniaxial, and its range of movement is in only one plane.

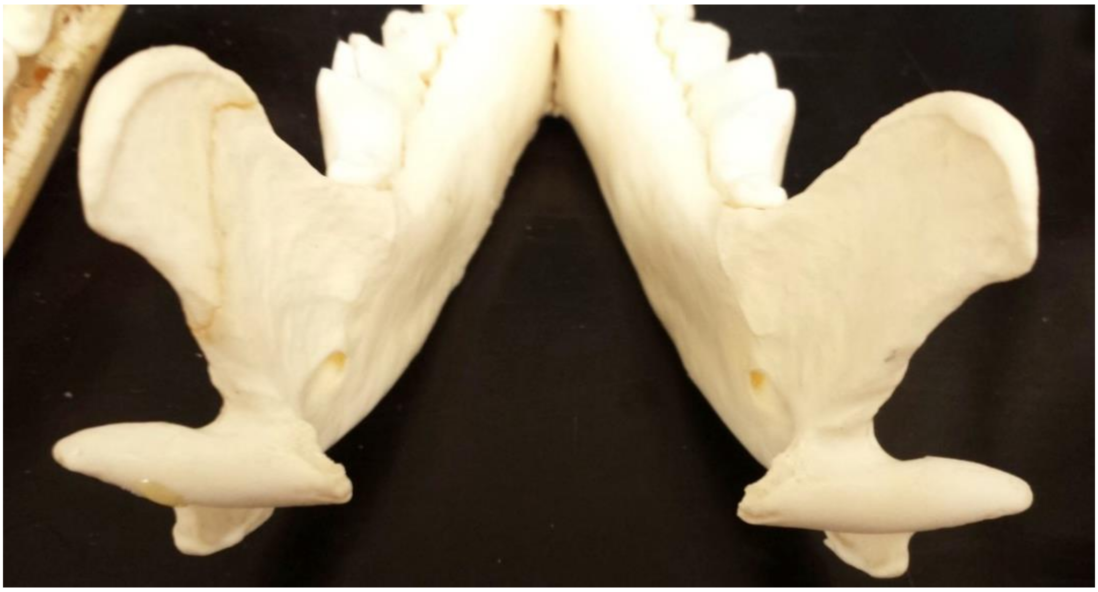
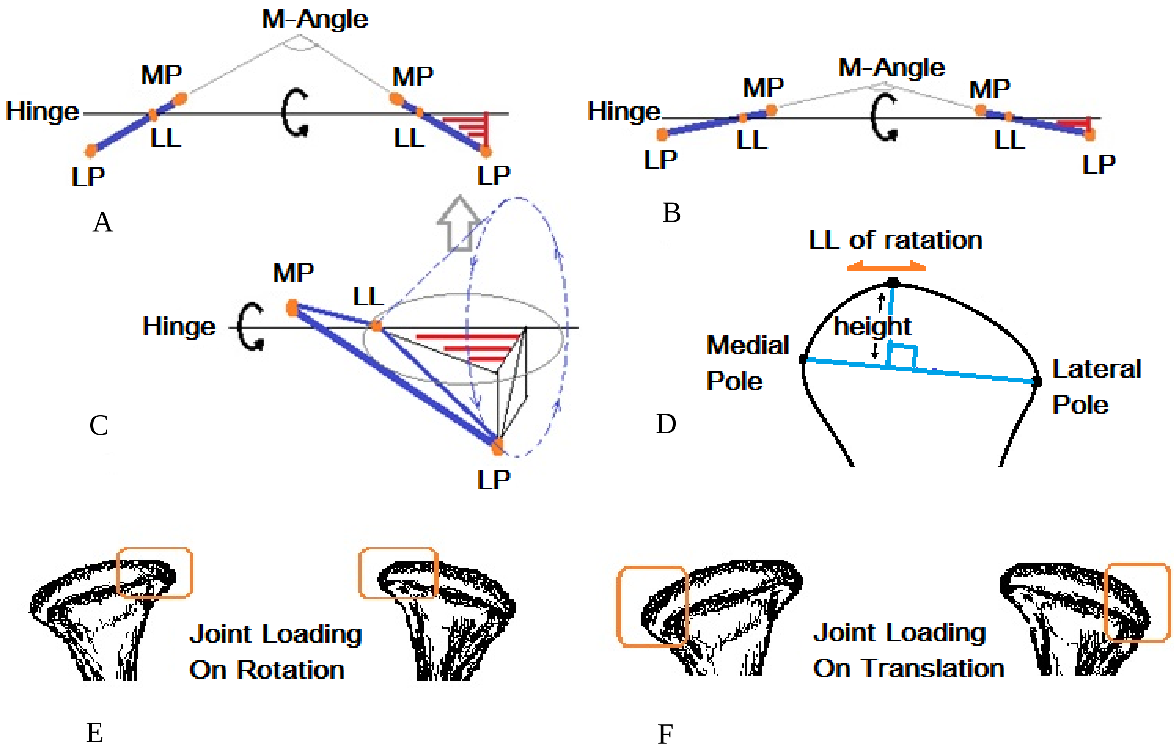


Fig. 5.1. Hinge shape TMJs of a carnivore.

Becker (2011) suggested that the location of loading of the human condyle head shifts from the medial part to the top or the lateral part, while the jaw starts the translation movement after a



LL: location of loading; LP: lateral pole of the condyle; MP: medial pole of the condyle;

A: the mediolateral axis with small M-Angle during hinging movements projected in the horizontal plane. The line connected by the two LL of the condyles can be regarded as the hinging axis without any interference. Additionally, diagram A is the two-dimensional projection of diagram C which represents the three-dimensional motion.
B: the mediolateral axis with large M-Angle during hinging movements projected in the horizontal plane
C: the three-dimensional schematic diagram of the mediolateral axis during hinging movements. Given the same position of MP, LP and LL, smaller condylar height will lead to the relative smaller volume of the cone (dashed line) caused by the motion if LL is close to the summit of condyle head (Fig. D).
D: adapted from Kinzinger, Kober and Diedrich (2007).
E & F: reproduced by Ao Sun from “Guidance of the patient’s mandible during centric relation arc of closure analysis and/or load testing. © 2010 Wolters Kluwer Health/Lippincott Williams and Wilkins”, cited by Becker, I. (2011). Comprehensive occlusal concepts in clinical practice. Oxford, UK: Wiley-Blackwell.

Fig. 5.2. Schematic diagram of relationship between mediolateral axis of condyle and M-Angle in hinging movements.

hinge movement (Fig. 5.2. E and F). Thus, during hinging movements, the most lateral point of the lateral pole is inclined to proceed over a longer distance, or a greater capacity of the fossa is necessary to accommodate the dimension of the trajectory of all the condyle surfaces in the patients with smaller M-Angle when other conditions are fixed (Fig. 5.2). With a small M-Angle, loading could take place at the lateral part of the condyle in rotation if the fossa is not suitable for the required volume (Fig 5.2). The flattened condylar head might result from the frequent alternation of hinging and translation movements in the transitional area, or a smaller condylar height of the head could be compensation for the demand on extra volume of the fossa.

On the other hand, Colombo, Palla and Gallo (2008) proposed that there were two types of stress field (location of disk-compressive areas) paths that occurred during opening (Fig. 5.3): (1) medial pole to lateral pole (ML) and (2) lateral pole to medial pole (LM), and they accordingly constructed two types of the model of condyle.

It was suggested that the condyle of the LM type model was likely to be flatter and the fossa deeper, whereas the ML type obtained a more rounded-shape condyle and flat fossa; however, the M-Angle in their study was set at 150° for the models without further description (Palla & Gallo, 2008). Because the author of the present study believes that, from the standpoint of efficiency, the greater displacement of the mandibular anterior teeth is dominated by the rotation of mandible around the hinging axis of TMJs other than the translation of mandible, hinging movements are supposed to be the dominant motion in both ML and LM paths during opening. Hence, the flatter-style LM condyle could result from the disharmony between the condyle head and the fossa during rotation. Further, Palla and Gallo (2008) found that in the LM group the gap between the lateral part of the condyles and fossae was smaller, which was attributed either/and to the thinner or degenerated disk, to the anatomical discrepancies between

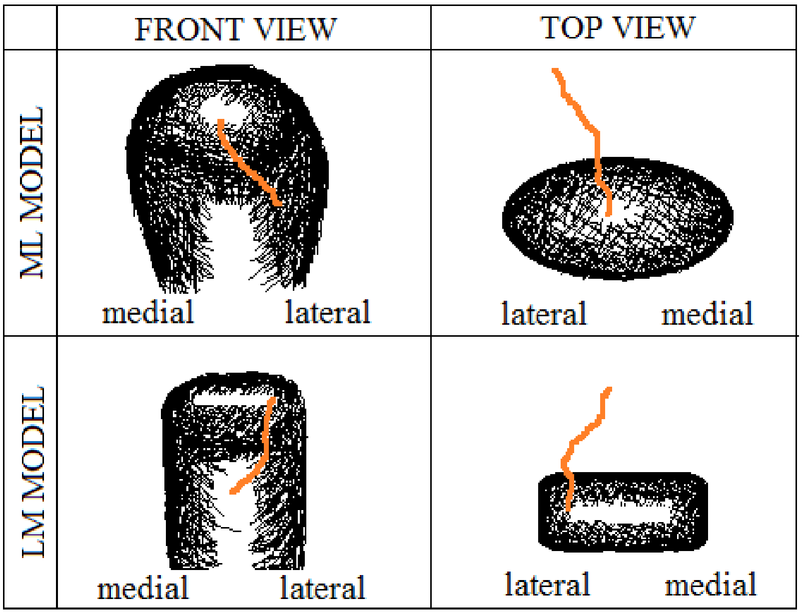


Fig. 5.3. Condyle models of two types of stress field paths
"Reproduced by Ao Sun from Colombo, V., Palla, S., & Gallo, L. M. (2008). Temporomandibular joint loading patterns related to joint morphology: A theoretical study. *Cells Tissues Organs*, 187(4), 295–306."

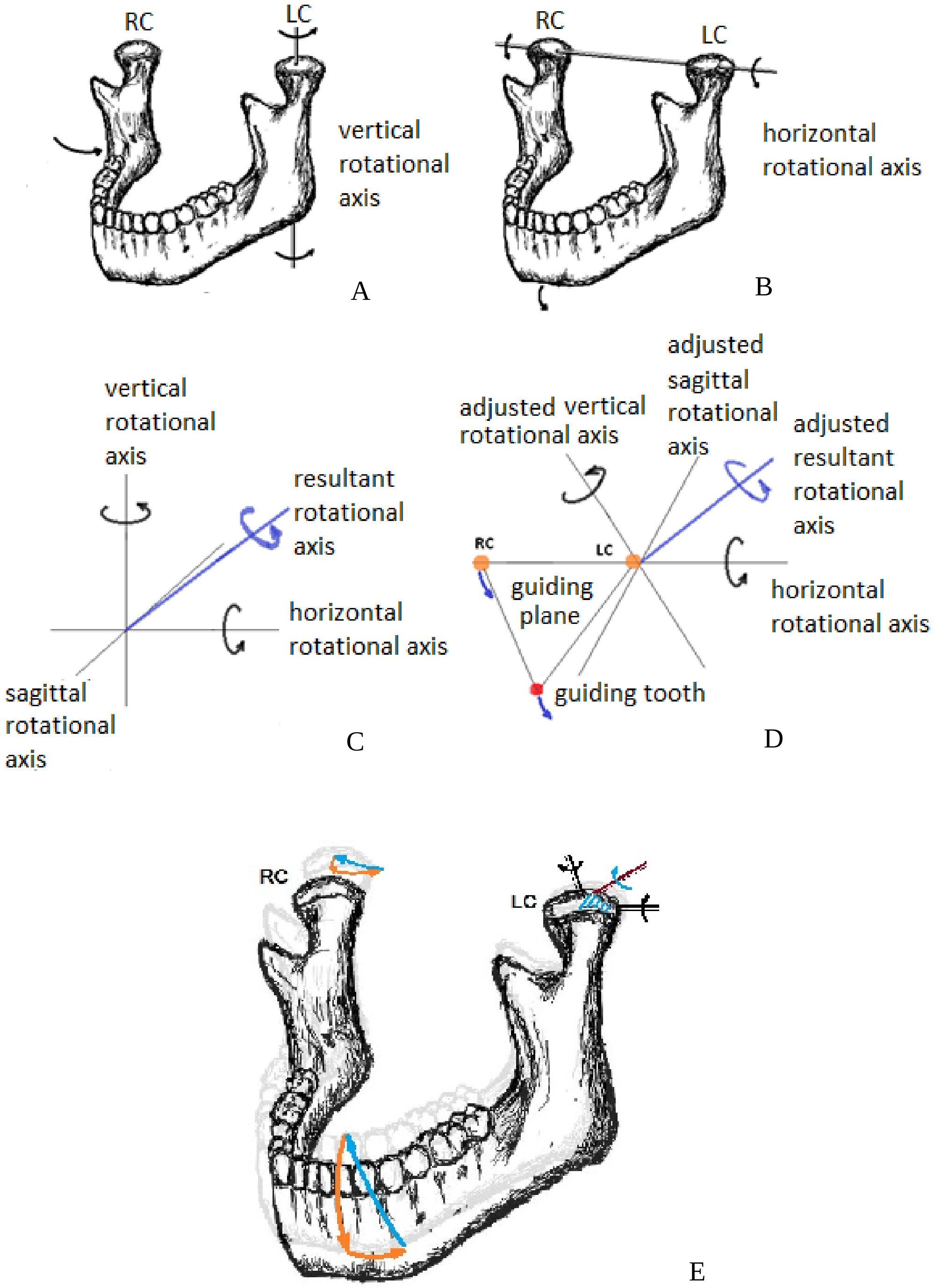
the lateral and medial parts, or to the greater angle of the medial-lateral axis of the condylar head to the transversal direction (the smaller M-Angle in the present study).

That some specific locations of resorption in condyles of osteoarthritic TMJs, such as on the anterior surface of the lateral pole and the posterior surface of the medial pole, were found (Cevidanes *et al*., 2010) also implied the particular part of condyle head inclined to be affected, and this might be due to stress during function with the above explanation.

5.4 View from Biomechanics

Felson *et al.* (2000) illustrated that the development of knee osteoarthritis might be related to overweight. They studied the association of overloading the knee (due to overweight) with the compromised cartilage and other contiguous tissues, and found that 1 lb. of weight gain could cause a 2-3 lb. increment increase in the overall force across the knee in a single-leg stance. Hence, it may be speculated that TMJs similarly can be injured by extra frictional or plowing force from overloading during the movement of the mandible. The plausible mechanism of TMJ overloading may include but is not limited to several elements: (1) the location of loading of condyles during the movement of the mandible, (2) the magnitude of the biting force and (3) the vulnerability of certain parts in the masticatory system, e.g., tooth crack, alveolar bone resorption, tooth mobility, etc.

Becker (2011) mentioned that the lateral part of the condyle is involved with the jaw's open-close movements. Usually, crushing or grinding of food by the molars is fulfilled during the latero-mediotrusive movement of the mandible within a chewing stroke; however, in the unilateral occlusal motion (Fig. 5.6), a pivotal characteristic of mammalian mastication (Langenbach & Van Eijden, 2001), the location of loading of the condyle is not clear. Although the translation component of the latero-mediotrusive movement remains unexplored, the role of the lateral part of the condyle in the rotational motions is proposed by the author of the present study as follows. All the hard structures are assumed to be rigid, and the buffering effect from ligaments is neglected.



RC: right condyle, LC: left condyle, Guiding plane: built by RC, LC and the guiding tooth (Figs. A and B reproduced by Ao Sun from Okeson, 2008).

Fig. 5.4. Rotational axis and guiding plane during mediotrusive or latertrusive movements.

The hinging movements of a condyle comprise horizontal and vertical axes rotation with respect to that condyle (Fig. 5.4 A and B), while sagittal axis rotation is almost impossible because of the restraint imposed by the ligaments and musculature of the contralateral TMJ. Additionally, the displacement of a point around the third axis can be fulfilled by the compound rotation around the other two axes in sequence. Since the teeth are located anteriorly and inferiorly to the condyles, the coordinate system with the guiding plane basing on the two condyles and the guiding tooth is adjusted with some degree of rotation around the horizontal axis (Fig. 5.4 D). Therefore, the adjusted resultant rotational axis of the relative coordinate system is anteriorly and laterally inclined, so the functional part of the condyle during resultant rotation may be at the anterior and lateral part of the condyle (Fig. 5.4 E). Fig. 5.5 demonstrates the differing performances of the working side and balancing side condyles with respect to fossae during the closing phase (Palla, Gallo & Gössi, 2003), which indicates that the balancing condyle traveled a longer distance than did the working one during the same period from position 2 (namely, the different linear velocity of the two condyles during function), so that a resultant rotational axis can be speculated near the working condyle.

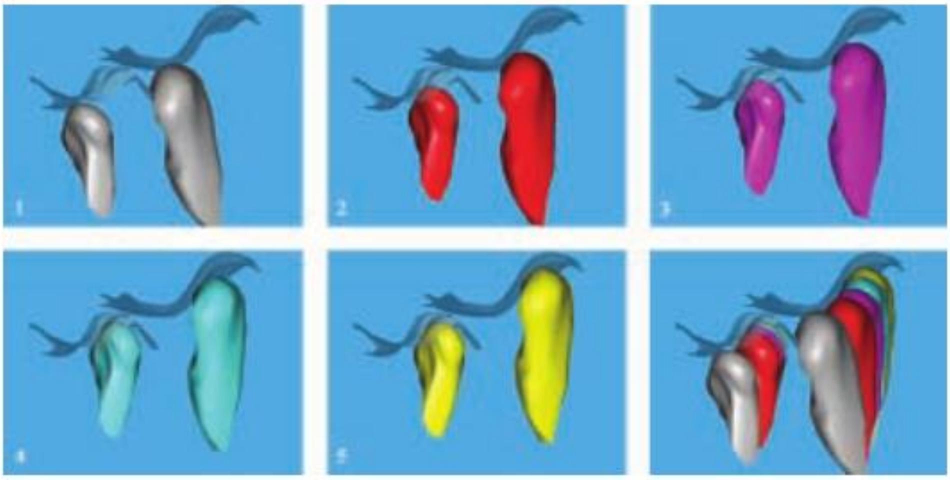


Fig. 5.5. Different performance of working side (left) and balancing side condyles during closing phase.

"Reprinted from Orthodontics & Craniofacial Research, 6(s1), Palla, S., Gallo, L. M., & Gössi, D., Dynamic stereometry of the temporomandibular joint, Page 42, (2003), with permission from John Wiley and Sons."

Fig. 5.6 illustrates the mandible chewing plots projected on the frontal plane (Gibbs *et al.*, 1981). The closing tracks can be divided into two segments: (1) the segment of mediotrusive movement without tooth contact (without closing phase) and (2) the segment of mediotrusive movement from initial tooth contact to the intercuspal position (closing phase). In the first, the plots of good occlusion proceeded smoothly during the two segments in a specific range of orientation, while the tracks of the other one obviously can be defined into two parts and sharp turns occurred between the two segments. With the assumption of resultant rotation, the former mandible seemed to rotate well during closing phase around the resultant axis of the working condyle; however, for the other subject, there was a standstill and a change of orientation of the tracks after the guiding tooth was contacted. One thus can assume that the latter mandible was rotating roughly along with two axes sequentially through the working-side condyle (horizontal axis – segment 1 and vertical axis – segment 2, respectively) because of the absence of a good functional guiding tooth.

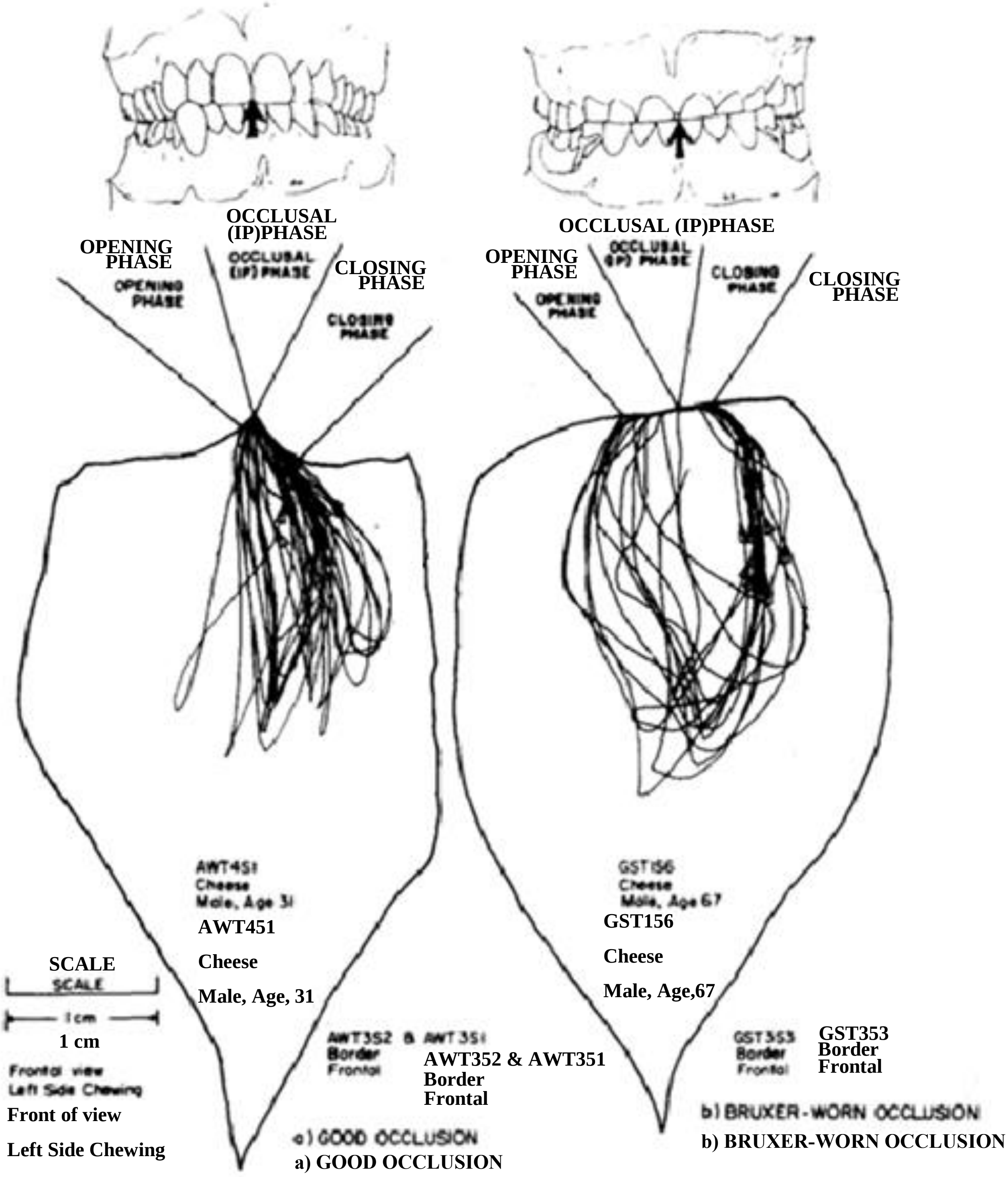


Fig. 5.6. Plots of chewing strokes of mandible movements.
“Reprinted from Occlusal forces during chewing-influences of biting strength and food consistency, 46(5), Gibbs, C. H., Mahan, P. E., Lundeen, H. C., Brehnan, K., Walsh, E. K., Sinkewiz, S. L., & Ginsberg, S. B., The Journal of prosthetic dentistry, Page 563, (1981), with permission from Elsevier,” and the additional text added by Ao Sun in the image is to assist with legibility of the original text.

Palla, Gallo and Gossi (2003) stressed that the shear force generated during joint movements and loaded onto the cartilage could be the reason for cartilage wear. Liu *et al*. (2010) reported that 62 out of 162 cases of disc perforation were located at the lateral-posterior part of the disc (Fig. 5.7). From their observation, one can conclude that about 85% of disc perforation was located at the lateral 2/3 of the disc and that the incidence of perforation tended to decrease gradually from the lateral-posterior part to the anterior and medial borders of the discs. Therefore, the location of disc perforation in TMJs may indicate the main part of the traction force being applied on the condyle, and thus the corresponding invaded location of the disc.

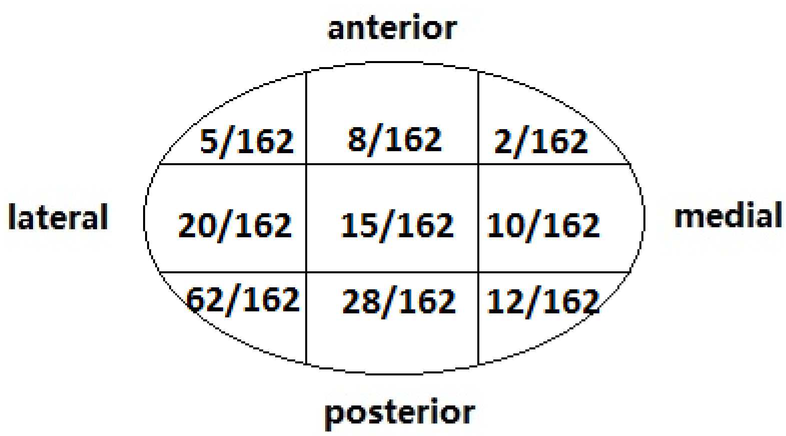
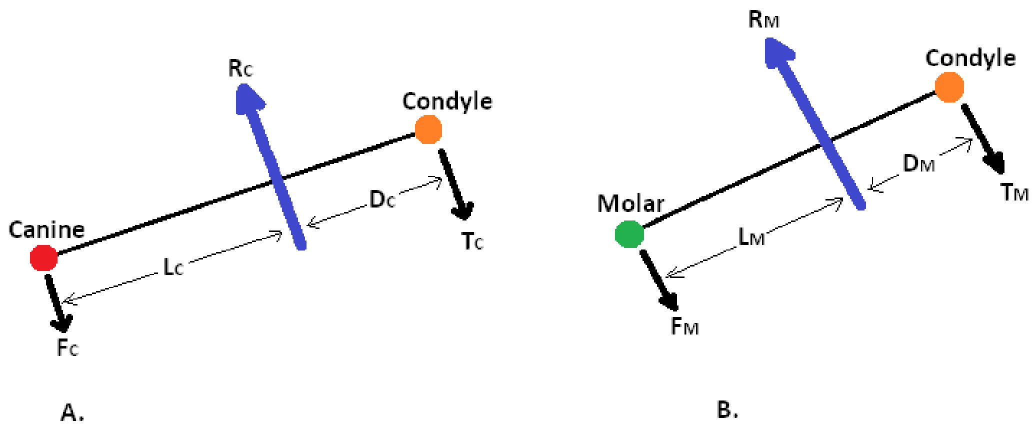


Fig. 5.7. "Disc perforation location in different parts, with the disc being divided into nine parts under arthroscopy" reproduced by Ao Sun from Liu *et al*. (2010).

While the lateral part of the condyle could be the location of functional loading, the occurrence of high magnitude force is another implicated factor and periodontal receptors may play an essential role in the regulation of the magnitude of force. First, the periodontal receptors in posterior teeth are more insensitive than those in the anterior teeth. Johnsen, Svensson and Trulsson (2007) illustrated that the perception force on teeth (the force needed to hold half a peanut between teeth) increases from the anterior to the posterior teeth: 0.6 N for the incisor and 0.77 N for the canine, whereas the force is 1.74 N for the first molar. Second, different biting forces may result from the various guiding teeth, and thus so do the corresponding forces loaded on TMJs. Bakke (1993) proposed a theory that there were two types of pressoreceptors in the periodontal ligaments influencing the biting force: (1) low-threshold receptors that could ignite the activity of the elevator muscles and (2) high-threshold receptors that could exert an inhibitory effect on the muscles when the biting force reached the magnitude of limit. Accordingly, if the pressoreceptors in the periodontal ligaments of molars are far more tolerant than those of canines, the higher magnitude of the biting force should be generated during the lateral-mediotrusive movement with posterior guidance, regardless of the smaller arm of force at molars than at canines (Fig. 5.8). In other words, the self-protective valve of the masticatory system with posterior guidance will become insensitive or silent; moreover, the ipsilateral TMJ can be affected by hyperactive elevator muscles in the repetitive chewing strokes after the adaptive capacity of the TMJ is overtaken due to the overloading. In addition, Williamson and Lundquist (1983) provided electromyogram evidence that the temporal and masseter muscles on the working side can be activated by the posterior contacts during latertrusive movements, and that canine guidance can reduce the activity of the elevator muscles.

The robustness of the whole system with respect to overloading depends on the weakest link of the chain, which means that the most vulnerable part of the system will be the first to be invaded. Other than TMJ issues, tooth break, root fracture, periodontal diseases, alveolar bone resorption and muscle pain could also be consequences of overloading. Ratcliff, Becker and Quinn (2001) reported that excursive interferences were related to the cracks in teeth; Gianelly (1969) described the mechanism of force-induced alveolar bone resorption; and Ishigaki *et al*. (2006) stated that abnormal chewing patterns could cause increased mobility of specific teeth. Once some part comes into failure – for example, the loss of a guiding molar – with the change of the occlusal pattern the whole system is supposed to rebuild the equilibrium with the rest of the components until breakdown happens again as a consequence of the similar harmful conditions. Therefore, from the stance of biomechanics, it would be useful to emphasize the role of overloading in the aetiology of the above dental diseases.



R_C: resultant biting force with canine as guiding tooth
R_M: resultant biting force with molar as guiding tooth
F_C: force applied on guiding canine
F_M: force applied on guiding molar
T_C: force applied on condyle with canine as guiding tooth
T_M: force applied on condyle with molar as guiding tooth
L_C, D_C, L_M, D_M: arms of relative force

Suppose a situation wherein the mandible stops when the guiding teeth contact with the magnitude at the high-threshold of the pressoreceptors, then:

$$F_C*L_C = T_C*D_C \text{ and } F_M*L_M = T_M*D_M;\ R_C= F_C+T_C,\ R_M=F_M+T_M$$

If $F_M \gg F_C$ and the difference between L_C and L_M, D_C and D_M are neglected, then $F_M*L_M \gg F_C*L_C$. Thus, $T_M \gg T_C$, and $R_M \gg R_C$.

Fig. 5.8. Schematic diagram of force analysis about biting force and force applied on guiding teeth and condyles in two dimensions.

To sum up: Inappropriate laterotrusive or mediotrusive guiding teeth resulting from detrimental teeth relationships that can be embodied by excessive overbite or overjet or other dentofacial characteristics, may be associated with TMJ issues. In the present study, lower-height condyles statistically are related to greater overbite and overjet, which indicates that Class II Division I patients could be a high-risk group with TMJ problems. This finding is not necessarily controversial with that in the study by Krisjane *et al.* (2012) regarding higher prevalence of degenerative bony findings in Class III patients under severe conditions, because the guiding teeth could be similar to those of Class II patients. If the conditions portfolio or some features of the Class II and Class III subjects are – a combination of posterior guidance in mediotrusive and laterotrusive movements; lack of anterior contacts; greater maxillary-mandibular discrepancies of Monson's Sphere; and so on – similar morphologic changes of condyles may take place in both groups.

CHAPTER 6 CONCLUSION, LIMITATIONS AND FUTURE WORK

6.1 Overview

All three objectives of this thesis have been accomplished.

1. The general regression model was performed to measure the Monson's Sphere of the dentitions with respect to the TMJs, and the general average mandibular radius of the 54 sample subjects (Chinese) was 85.69 mm.
2. The correlation among the specific dentofacial factors and condylar height was evaluated by statistical analysis. By clinical description, the profile of the patients with lower-value condylar height comprised larger ANB, Overjet, Overbite, closer distance from the mandibular incisors to the condyles (greater B-Angle) and a large discrepancy between the dentition patterns (smaller RMM).
3. The biomechanical mechanism of the correlation was speculated in terms of the functional movements of the mandible. A detrimental teeth relationship can be embodied by excessive overbite or overjet and/or other dentofacial characteristics, and this relationship usually leads to inappropriate laterotrusive or mediotrusive guiding teeth and sequent overloading. Thus, overbite or overjet or other dentofacial characteristics could be found to be associated with TMJ issues.

6.2 Conclusion

1. Both the mandibular and maxillary Monson's Spheres can be evaluated with the linear regression (based on formula 3.2), including the radii and the center of the sphere. The average radius of the mandible Monson's Sphere is less than 100mm, and of the radii of

the 54 subjects only 3 are around 100 mm; however, the average distance between the two summits of the condyles is 100.87 mm.

2. Some dentofacial characteristics are related to the condyle conditions. The Angle Classification Class II Division I group who have the low height condyles seems to be the high-risk population, and M-angle of the condyles is important in the motion analysis of condyles. However, if people in other categories exhibit features in common such as a combination of posterior guidance in mediotrusive and laterotrusive movements, a lack of anterior contacts, or greater maxillary-mandibular discrepancies of Monson’s sphere, the relative condyles may be at high risk of morphologic changes as well. In other words, a combination of dentofacial conditions may narrow the range of variables and help to detect the vulnerable TMJs.

6.3 Contribution (clinical significance)

1. The general profile of the occlusal curves in the Chinese population in this study can be illustrated with the radii of both the maxillary and mandibular Monson’s Sphere.
2. The relationship between specific dentofacial variables and TMJ features might provide an approach to identify the high-risk group with the condyle shape changes, which could be beneficial to future occlusal therapy or TMD treatment.
3. This study might lay the groundwork for future research on the relationship between occlusion and TMJs, and on studies of the biomechanical rationale behind the overloading applied on TMJs during the complex movement of the mandible.

6.4 Limitations

1. Because this study is based solely on a cross-sectional investigation and observation of the CT DICOMs, other information such as guidance patterns, molar relationships, posterior

crossbite and interference during mediotrusive and laterotrusive sliding cannot be verified. The unilateral condyle aspects may be highly associated with the ipsilateral dental conditions.

2. The subjects are not traceable; thus, further history cannot be assessed on review.
3. A larger sample size is desirable so that more independent variables can be run at the same time in statistics analysis.
4. The ANB angulation was calculated by the three-dimensional coordinates of the four landmarks (points S, N, A and B), so the values might differ from those measured via cephalometric radiographs, which is the projection in two dimensions of the same landmarks.
5. The estimation of the mediolateral axes angulation (M-Angle), measured directly from the horizontal slice in Mango, might differ from the actual because (1) the field of Mango cannot accommodate the auxiliary lines extending from the two mediolateral axes, (2) the two mediolateral axes are not in the same horizontal plane in three-dimension, and (3) the two mediolateral axes are not parallel to the horizontal slice.
6. More evidence is needed to verify the mandibular motion in a three-dimensional space and the role of the working-side condyle in the movements; further, it is necessary to perform moment equilibrium analysis in a three-dimensional space in order to estimate the force applied on specific locations, such as the condyles on both sides and the guiding tooth.

6.5 Future Work

Necessary future work regarding the correlation of the occlusion and TMJs includes:

1. Future work should collect oral conditions such as guiding teeth, molar interference and central relation to be coupled with the CT data of the related patients.

2. The longitudinal history of the patients should be reviewed.
3. Future work should devise a way to record the mandibular motion so as to confirm the role of motion of condyles.

REFERENCES

Ahmad, M., Hollender, L., Anderson, Q., Kartha, K., Ohrbach, R., & Truelove, E. L., *et al*. (2009). Research diagnostic criteria for temporomandibular disorders (rdc/tmd): development of image analysis criteria and examiner reliability for image analysis. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontology, 107*(6), 844–860.

Andrews, L. F. (1972). The six keys to normal occlusion. *American journal of orthodontics, 62*(3), 296–309.

Ali, I. M., Yamada, K., Alkhamrah, B., Vergara, R., & Hanada, K. (2003). Relationship between occlusal curvatures and mandibular deviation in orthodontic patients with temporomandibular disorders. *Journal of Oral Rehabilitation, 30*(11), 1095–1103.

Atit, M., Darda, M., Deshmukh, S., Naik, C., Rahalkar, J., & Subramanian, V. (2013). Mean values of Steiner, Tweed, Ricketts and McNamara analysis in Maratha ethnic population: A cephalometric study. *APOS Trends in Orthodontics*, 3(5), 137–151.

Baydaş, B., Yavuz, I., Atasaral, N., Ceylan, I., & Dağsuyu, I. M. (2004). Investigation of the changes in the positions of upper and lower incisors, overjet, overbite, and irregularity index in subjects with different depths of curve of spee. *Angle Orthodontist, 74*(3), 349–355.

Bakke, M. (1993). Mandibular elevator muscles: physiology, action, and effect of dental occlusion. *Scandinavian Journal of Dental Research*, 101(5), 314–331.

Becker, I. (2011). Comprehensive occlusal concepts in clinical practice. Oxford, UK: Wiley-Blackwell.

Bonwill, W. G. A. (1884). Geometrical and mechanical laws of articulation. *Trans Odont Soc Penn, 1885*, 119–133.

Celić, R., Jerolimov, V., & Pandurić, J. (2002). A study of the influence of occlusal factors and parafunctional habits on the prevalence of signs and symptoms of tmd. *International Journal of Prosthodontics, 15*(1), págs. 43–48.

Cevidanes, L. H. S., Hajati, A. K., B. Paniagua, M. S., Lim, P. F., Walker, D. G., & Palconet, G., *et al*. (2010). Quantification of condylar resorption in temporomandibular joint osteoarthritis. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics, 110*(1), 110–117.

Chisnoiu, A. M., Picos, A. M., Popa, S., Chisnoiu, P. D., Lascu, L., & Picos, A., *et al*. (2015). Factors involved in the etiology of temporomandibular disorders - a literature review. *Clujul Medical, 88*(4), 473–478.

Ciancaglini, R., Gherlone, E. F., & Radaelli, G. (2003). Unilateral temporomandibular disorder and asymmetry of occlusal contacts. *Journal of Prosthetic Dentistry, 89*(2), 180–185.

Cheon, S. H., Park, Y. H., Paik, K. S., Ahn, S. J., Hayashi, K., & Yi, W. J., *et al*. (2008). Relationship between the curve of spee and dentofacial morphology evaluated with a 3-dimensional reconstruction method in korean adults. *American journal of orthodontics and dentofacial orthopedics: official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics*, *133*(5), 7–14.

Christensen, F. T. (1958). The effect of Bonwill's triangle on complete dentures. *The Journal of Prosthetic Dentistry, 9*(5), 791–796.

Clark, G. T., Tsukiyama, Y., Baba, K., & Watanabe, T. (1999). Sixty-eight years of experimental occlusal interference studies: what have we learned? *The Journal of Prosthetic Dentistry, 82*(6), 704–713.

Colombo, V., Palla, S., & Gallo, L. M. (2008). Temporomandibular joint loading patterns related to joint morphology: A theoretical study. *Cells Tissues Organs*, 187(4), 295–306.

Curve of Spee. (n.d.) Mosby's Medical Dictionary, 8th edition. (2009). Retrieved from http://medicadictionary.thefreedictionary.com

Curve of Wilson. (n.d.) Mosby's Medical Dictionary, 8th edition. (2009). Retrieved from http://medicaldictionary.thefreedictionary.com

Dawson, P. E. (1999). Position paper regarding diagnosis, management, and treatment of temporomandibular disorders. *Journal of Prosthetic Dentistry, 81*(2), 174–178.

Dawson, P. E. (2007). Functional occlusion: from TMJ to smile design. St. Louis, MO: Mosby.

De Praeter, J., Dermaut, L., Martens, G., & Kuijpers-Jagtman, A. M. (2002). Long-term stability of the leveling of the curve of Spee. *American journal of orthodontics and dentofacial orthopedics, 121*(3), 266–272.

Ettinger, S, J., & Feldman, E, C. (2009). Text of veterinary internal medicine, seventh edition. St. Louis, MO: Saunders.

Facial Pain. (n.d.) National Institute of Dental and Craniofacial Research. Retrieved from: http://www.nidcr.nih.gov/DataStatistics/FindDataByTopic/ FacialPain/ (the page last updated on March 07, 2014).

Farella, M., Michelotti, A., Eijden, T. M. G. J. V., & Martina, R. (2002). The curve of spee and craniofacial morphology: a multiple regression analysis. *European Journal of Oral Sciences, 110*(4), 277–281.

Farella, M., Michelotti, A. G., Milani, S., & Martina, R. (2007). Unilateral posterior crossbite is not associated with tmj clicking in young adolescents. *Journal of Dental Research, 86*(2), 137–141.

Ferrario, V. F., Sforza, C., & Miani Jr, A. (1997). Statistical evaluation of Monson's sphere in healthy permanent dentitions in man. *Archives of oral biology, 42*(5), 365–369.

Ferrario, V. F., Sforza, C., Poggio, C. E., Serrao, G., & Colombo, A. (1999). Three-dimensional dental arch curvature in human adolescents and adults. *American journal of orthodontics and dentofacial orthopedics, 115*(4), 401–405.

Fueki, K., Yoshida, E., & Igarashi, Y. (2013). Association between occlusal curvature and food comminution and mixing in human young adults with permanent dentitions. *Archives of Oral Biology, 58*(4), 377–383.

Fueki, K., Yoshida, E., Okano, K., & Igarashi, Y. (2013). Association between occlusal curvature and masticatory movements with different test foods in human young adults with permanent dentitions. *Archives of oral biology*, *58*(6), 674–680.

Gianelly, A. A. (1969). Force-induced changes in the vascularity of the periodontal ligament. *American Journal of Orthodontics,* 55(1), 5–11.

Gibbs, C. H., Mahan, P. E., Lundeen, H. C., Brehnan, K., Walsh, E. K., & Sinkewiz, S. L., Ginsberg, S. B. (1981). Occlusal forces during chewing—influences of biting strength and food consistency. *Journal of Prosthetic Dentistry,* 46(5)*,* 561–567.

Gray, R. J. M., & Al-Ani, M. Z. (2011). Temporomandibular disorders: a problem-based approach. West Sussex, UK: Wiley-Blackwell.

Ha, M. H., Kim, Y. I., Park, S. B., Kim, S. S., & Son, W. S. (2013). Cone-beam computed tomographic evaluation of the condylar remodeling occurring after mandibular set-back by bilateral sagittal split ramus osteotomy and rigid fixation. T*he Korean Journal of Orthodontics*, *43*(6), 263–270.

Herring, S. W. (2003). TMJ anatomy and animal models. *Journal of musculoskeletal & neuronal interactions*, *3*(4), 391.

Hiiemäe, K. M. (1967). Masticatory function in the mammals. *Journal of dental research,* 46(5), 883–893.

Ishigaki, S., Kurozumi, T., Morishige, E., & Yatani, H. (2006). Occlusal interference during mastication can cause pathological tooth mobility. *Journal of Periodontal Research*, 41(3), 189–192.

Ito, H., Okimoto, K., Mizumori, T., Terada, Y. & Maruyama, T. (1997). A clinical study of the relationship between occlusal curvature and craniomandibular disorders. *International Journal of Prosthodontics*, *10*(1), 78–82.

Jenkins, S. (2005). Sports Science Handbook: the essential guide to kinesiology, sport and exercise science, Volume 2: I-Z. Essex, UK: Multi-Science Publishing.

John, M. T., Hirsch, C., Drangsholt, M. T., Mancl, L. A., & Setz, J. M. (2002). Overbite and overjet are not related to self-report of temporomandibular disorder symptoms. *Journal of Dental Research, 81*(3), 164–169.

Johnsen, S. E., Svensson, K. G., & Trulsson, M. (2007). Forces applied by anterior and posterior teeth and roles of periodontal afferents during hold-and-split tasks in human subjects. *Experimental Brain Research,* 178(1), 126–134.

Kagaya, K., Minami, I., Nakamura, T., Sato, M., Ueno, T., & Igarashi, Y. (2009). Three-dimensional analysis of occlusal curvature in healthy Japanese young adults. *Journal of oral rehabilitation, 36*(4), 257–263.

Kahn, J., Tallents, R. H., Katzberg, R. W., Moss, M. E., & Murphy, W. C. (1998). Association between dental occlusal variables and intraarticular temporomandibular joint disorders: horizontal and vertical overlap. *The Journal of prosthetic dentistry, 79*(6), 658–662.

Kahn, J., Tallents, R. H., Katzberg, R. W., Ross, M. E., & Murphy, W. C. (1999). Prevalence of dental occlusal variables and intraarticular temporomandibular disorders: molar relationship, lateral guidance, and nonworking side contacts. *Journal of Prosthetic Dentistry, 82*(4), 410–415.

Kanavakis, G., & Mehta, N. (2013). The role of occlusal curvatures and maxillary arch dimensions in patients with signs and symptoms of temporomandibular disorders. *Angle Orthodontist, 84*(1), 96–101.

Katsavrias, E. G. (2006). Morphology of the temporomandibular joint in subjects with class ii division 2 malocclusions. *American Journal of Orthodontics and Dentofacial Orthopedics, 129*(4), 470–478.

Katsavrias, E. G., & Halazonetis, D. J. (2005). Condyle and fossa shape in class ii and class iii skeletal patterns: a morphometric tomographic study. *American Journal of Orthodontics & Dentofacial Orthopedics, 128*(3), 337–346.

Kawagoe, T., Onodera, K., Tokiwa, O., Sasaguri, K., Akimoto, S., & Sato, S. (2009). Relationship between sleeping occlusal contact patterns and temporomandibular disorders in the adult japanese population. *International Journal of Stomatology & Occlusion Medicine*, *2*(1), 11–15.

Kinzinger, G., Kober, C., & Diedrich, P. (2007). Topography and morphology of the mandibular condyle during fixed functional orthopedic treatment -- a magnetic resonance imaging study. *Journal of Orofacial Orthopedics*, *68*(2), 124–147.

Krisjane, Z., Urtane, I., Krumina, G., Neimane, L., & Ragovska, I. (2012). The prevalence of TMJ osteoarthritis in asymptomatic patients with dentofacial deformities: a cone-beam CT study. *International journal of oral and maxillofacial surgery*, *41*(6), 690–695.

Langenbacn, G. E. J., & Van Eijden, T. M. G. J. (2001). Mammalian feeding motor patterns. *American Zoologist*, 41(6), 1338–1351.

Lauriti, L., Motta, L. J., Godoy, C. H. L. D., Politti, F., Mesquita-Ferrari, R. A., & Fernandes, K. P. S., *et al*. (2014). Influence of temporomandibular disorder on temporal and masseter muscles and occlusal contacts in adolescents: an electromyographic study. *Bmc Musculoskeletal Disorders, 15*(1), 1–8.

Liu, X. M., Zhang, S. Y., Yang, C., Chen, M. J., Cai, X. Y., Haddad, M. S., … Chen, Z. Z. (2010). Correlation between disc displacements and locations of disc perforation in the temporomandibular joint. *Dentomaxillofacial Radiology*, 39(3), 149–156.

Lynch, C. D., & McConnell, R. J. (2002). Prosthodontic management of the curve of Spee: use of the Broadrick flag. *The Journal of prosthetic dentistry*, 87(6), 593–597.

Ma, X., Fang, B., Dai, Q., Xia, Y., Mao, L., & Jiang, L. (2013). Temporomandibular joint changes after activator appliance therapy: a prospective magnetic resonance imaging study. *Journal of Craniofacial Surgery, 24*(4), 1184–1189.

Manfredini, D. (2010). Current concepts on temporomandibular disorders. Berlin: Quintessence.

Mohlin, B., Axelsson, S., Paulin, G., Pietilä, T., Bondemark, L., & Brattström, V., *et al*. (2007). Tmd in relation to malocclusion and orthodontic treatment. *Angle Orthodontist, 77*(3), 542–548.

Mongini, F. (1980). Condylar remodeling after occlusal therapy. *The Journal of prosthetic dentistry*, *43*(5), 568–577.

Mongini, F. (1977). Anatomic and clinical evaluation of the relationship between the temporomandibular joint and occlusion. *The Journal of prosthetic dentistry, 38*(5), 539–551.

Monson, G. S. (1932). Applied mechanics to the theory of mandibular movements. *Dent Cosmos*, *74*, 1039–1053.

Nam, S. E., Park, Y. S., Lee, W., Ahn, S. J., & Lee, S. P. (2013). Making three-dimensional Monson's sphere using virtual dental models. *Journal of dentistry, 41*(4), 336–344.

Needles, J. W. (1923). Practical uses of the curve of spee. *Journal of the American Dental Association*, *10*(10), 918–927.

Okeson. (2008). Management of temporomandibular disorders and occlusion, 6th edition. St.

Louis, MO: Mosby.

Palla, S., Gallo, L. M., & Gössi, D. (2003). Dynamic stereometry of the temporomandibular joint. *Orthodontics & Craniofacial Research*, 6(s1), 37–47.

Pullinger, A. G., Seligman, D. A., & Gornbein, J. A. (1993). A multiple logistic regression analysis of the risk and relative odds of temporomandibular disorders as a function of common occlusal features. *Journal of Dental Research*, *72*(6), 968–979.

Pullinger, A. G., & Seligman, D. A. (2000). Quantification and validation of predictive values of occlusal variables in temporomandibular disorders using a multifactorial analysis. *Journal of Prosthetic Dentistry, 83*(1), 66–75.

Ratcliff, S., Becker, I. M., & Quinn, L. (2001). Type and incidence of cracks in posterior teeth. *Journal of Prosthetic Dentistry*, 86(2), 168–172.

Ré, J. P., Perez, C., Giraudeau, A., Ager, P., El Zoghby, A., & Orthlieb, J. D. (2008). Reconstruction of the curve of Spee. *Stomatologie, 105*(2), 29–32.

Ribeiro, E. C., Sanches, M. L., Alonso, L. G., Smith, R. L., RIBEIRO, E., SANCHES, M. & SMITH, R. (2015). Shape and Symmetry of Human Condyle and Mandibular Fossa. *Int. J. Odontostomat*, *9*(1), 65–72.

Sakaguchi, K., Uehara, S., Yagi, T., & Miyawaki, S. (2012). Relationship between occlusal curvatures and bite force in humans. *Orthodontic Waves, 71*(71), 79–84.

Schiffman, E., Ohrbach, R., Truelove, E., Look, J., Anderson, G., & Goulet, J. P., *et al*. (2014). Diagnostic criteria for temporomandibular disorders (dc/tmd) for clinical and research applications: recommendations of the international rdc/tmd consortium network* and orofacial pain special interest group†. *Journal of Oral & Facial Pain & Headache, 28*(1), 6–27.

Seligman, D. A., & Pullinger, A. G. (2000). Analysis of occlusal variables, dental attrition, and age for distinguishing healthy controls from female patients with intracapsular temporomandibular disorders. *Journal of Prosthetic Dentistry, 83*(1), 76–82.

Selaimen, C. M., Jeronymo, J. C., Brilhante, D. P., Lima, E. M., Grossi, P. K., & Grossi, M. L. (2007). Occlusal risk factors for temporomandibular disorders. *Angle Orthodontist, 77*(3), 471–477.

Sirona Dental Systems LLC. (n. d.). Galileos – a new dimension in 3D diagnosis. Retrieved from http://www.sironausa.com

Solberg, W. K., Bibb, C. A., Nordström, B. B., & Hansson, T. L. (1986). Malocclusion associated with temporomandibular joint changes in young adults at autopsy. *American Journal of Orthodontics*, 89(4), 326–330.

Spee, F. G., Biedenbach, M. A., Hotz, M., & Hitchcock, H. P. (1980). The gliding path of the mandible along the skull. *The Journal of the American Dental Association, 100*(5), 670–675.

Takayama, Y., Miura, E., Yuasa, M., Kobayashi, K., & Hosoi, T. (2008). Comparison of occlusal condition and prevalence of bone change in the condyle of patients with and without temporomandibular disorders. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontology, 105*(1), 104–112.

Tallents, R. H., Macher, D. J., Kyrkanides, S., Katzberg, R. W., & Moss, M. E. (2002). Prevalence of missing posterior teeth and intraarticular temporomandibular disorders. *The Journal of prosthetic dentistry, 87*(1), 45–50.

Veli, I., Ozturk, M. A., & Uysal, T. (2015). Curve of spee and its relationship to vertical eruption of teeth among different malocclusion groups. *American Journal of Orthodontics and Dentofacial Orthopedics, 147*(3), 305–312.

WANG, M. Q., CAO, H. T., LIU, F. R., Chen, C., & Li, G. (2007). Association of tightly locked occlusion with temporomandibular disorders. *Journal of oral rehabilitation*, *34*(3), 169–173.

Williamson, E. H., & Lundquist, D. O. (1983). Anterior guidance: its effect on electromyographic activity of the temporal and masseter muscles. *The Journal of Prosthetic Dentistry*, 49(6), 816–823.

Xu, H., Suzuki, T., Muronoi, M., & Ooya, K. (2004). An evaluation of the curve of Spee in the maxilla and mandible of human permanent healthy dentitions. *The Journal of prosthetic dentistry, 92*(6), 536–539.

Zarb, G. A., & Carlsson, G. E. (1999). Temporomandibular Disorders: Osteoarthritis. *Journal of orofacial pain, 13*(4), 295–306.

APPENDIX A

Approval from Bio-REB (Bio# 16-53)

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Approval

PRINCIPAL INVESTIGATOR
Chris Zhang

DEPARTMENT
Mechanical Engineering

Bio #
16-53

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
China
University of Saskatchewan
Saskatoon SK

SUB-INVESTIGATOR(S)
Dean Kolbinson

FUNDER(S)
UNFUNDED

TITLE
Protocol : Three Dimensional Analysis of Dental Curvatures with CT Data in Chinese Individuals

ORIGINAL REVIEW DATE	APPROVED ON	APPROVAL OF	EXPIRY DATE
	30-Mar-2016	revised Application to Access Existing Health Data for Research (rec'd March 30, 2016) Master list (rec'd March 30, 2016) Data Collection Sheet (rec'd March 30, 2016) Acknowledgment: Approval from Dental Clinic Dental Clinic patient consent form	29-Mar-2017

Delegated Review ☐ Full Board Meeting ☐

CERTIFICATION
The study is acceptable on scientific and ethical grounds. The Bio-REB considered the requirements of section 29 under the Health Information Protection Act (HIPA) and is satisfied that this study meets the privacy considerations outlined therein. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face) meeting. If a protocol has been reviewed at a full board meeting, a subsequent study of the same protocol may be reviewed through the delegated review process. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://research.usask.ca/for-researchers/ethics/index.php.

REB ATTESTATION
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Part 4 of the Natural Health Products Regulations and Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. Members of the Bio-REB who are named as investigators, do not participate in the discussion related to, nor vote on such studies when presented to the Bio-REB. This approval and the views of this REB have been documented in writing. The University of Saskatchewan Biomedical Research Ethics Board has been approved by the Minister of Health, Province of Saskatchewan, to serve as a Research Ethics Board (REB) for research projects involving human subjects under section 29 of The Health Information Protection Act (HIPA).

Gordon McKay, PhD., Chair
University of Saskatchewan
Biomedical Research Ethics Board

Please send all correspondence to:
Research Services and Ethics Office
Room 223 Thorvaldson Building
110 Science Place
Saskatoon, SK Canada S7N 5C9

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Approval
Study Amendment

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Chris Zhang	Mechanical Engineering	16-53

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
China University of Saskatchewan
Saskatoon SK

STUDENT RESEARCHER(S)
Ao (Robin) O. Sun

FUNDER(S)
UNFUNDED

TITLE
Correlation of Monson's sphere and some other dentofacial variables to temporomandibular joints (TMJs) in the Chinese population

APPROVAL OF	APPROVED ON	CURRENT EXPIRY DATE
Change of study title from "The Correlation of Monson's Sphere and Other Dentofacial Variables to Temporomandibular Joints (TMJs) Features in Chinese Individuals" to "Correlation of Monson's sphere and some other dentofacial variables to temporomandibular joints (TMJs) in the Chinese population"	12-Dec-2017	27-Feb-2018

Delegated Review ☒ Full Board Meeting ☐

IRB 1 Registration #00001471 ☐ IRB 2 Registration #00008358 ☐ Not Applicable ☒

CERTIFICATION
The University of Saskatchewan Biomedical Research Ethics Board (Bio-REB) has reviewed the above-named research study. The study was found to be acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face) meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://research.usask.ca/for-researchers/ethics/index.php.

REB ATTESTATION
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Part 4 of the Natural Health Products Regulations and Part C Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. Members of the Bio-REB who are named as investigators, do not participate in the discussion related to, nor vote on such studies when presented to the Bio-REB. This approval and the views of this REB have been documented in writing. The University of Saskatchewan Biomedical Research Ethics Board is constituted and operates in accordance with the current version of the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS 2 2014).

Gordon McKay, PhD., Chair
University of Saskatchewan
Biomedical Research Ethics Board

Please send all correspondence to:

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University of Saskatchewan
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STUDY CLOSURE FORM

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PART 1: IDENTIFICATION:	
Bio #: 16-53	**Protocol # (if applicable):**
Study Title: Correlation of Monson's sphere and some other dentofacial variables to temporomandibular joints (TMJs) in the Chinese population	
Principal Investigator and Supervisor: Chris Zhang	
Current Expiry Date: 2018-02-27	
Sponsor: N/A	**Funder:** N/A

PART 2: DECLARATION BY PRINCIPAL INVESTIGATOR:

The Principal Investigator assumes full responsibility for the information presented in this closure report and certifies that:

1. All of the information is accurate and complete as presented;
2. There is no further participant involvement, and all data collection, clarification and transfer is complete (including access to the participants' medical record);
3. For research involving secondary use of existing health data or biological materials, the acquisition of data is complete and/or no additional biological materials are being acquired.

Date the form was completed: 2017-12-11
Name of Person who completed the form: Ao (Robin) Sun

If form submitted on behalf of the PI:

Ao (Robin) Sun is authorized to prepare and submit this form on behalf of the Principal Investigator
Authorized person contact information:
Email: **Robin.sun@usask.ca** Phone: **306-514-1128**

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STUDY CLOSURE REPORT FORM
June 2015

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APPENDIX B

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